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FIRE PROPAGATION IN CONCURRENT FLOWS

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FIRE PROPAGATION IN CONCURRENT FLOWS

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Final Progress Report

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Building and Fire Research Laboratory
Gaithersburg, MD 20899

ABSTRACT

A research program has being conducted to study the mechanisms controlling the spread of flames in an oxidizing gas flow moving in the direction of flame propagation. During this reporting period research has been conducted to study the effect of the oxidizer flow characteristics on the concurrent flame spread over thick PMMA sheets. The parameters varied in the experiments are the oxidizer flow velocity, turbulence intensity and oxygen concentration, and the geometrical orientation (floor and ceiling). Their effect on the flame spread process is studied by measuring the rate of flame spread, flame length, surface heat flux, products of combustion and soot. The results of the experiments show that the combined effect of flow velocity, turbulence intensity, and oxygen concentration has a complex influence on the flame spread process. At low flow velocity, the flame spread rate increases monotonically with turbulence intensity. At high flow velocity, however, the flame spread rate increases with flow turbulence at low turbulence intensities, but it decreases at high turbulence intensity values. The effect is more pronounced at high oxygen concentration. These trends appear to be due to a strong influence of the turbulence intensity on the flame temperature and length, and on the heat flux from the flame to the solid fuel. Turbulence enhances mixing, which increases the flame temperature and then the heat flux. The effect of turbulence on the flame length comes from two opposing factors. In one hand the enhanced mixing results in a stronger reaction with faster reactant consumption, which tends to produce a shorter but hotter flame. On the other hand , the higher flame temperature results in an increased mass burning rate, which tends to increase the flame length. It appears that at low flow turbulence, the latter effect dominates and thus there is an increase in the flame length. As the turbulence level continues to rise, the reactant comsumption dominates, which leads to a decrease in the flame length. For the present experiments, the transition between the two regimes shifts from $u'/U = 5$ % at $U = 2.0$ m/s, to $u'/U = 15$ % at $U = 1.0$ m/s, and no transition point is observed at $U = 0.5$ m/s within our experimental conditions. The flame spread rate is the outcome of the combined effect of the flame length and the heat flux. Under all flow velocities and turbulence intensities, the flame spread rate increases with the oxygen concentration. For low oxygen concentrations, a linear dependence is observed between the flame spread rate and the oxygen concentration. For high oxygen concentrations, the dependence of the flame spread rate on the oxygen concentration follows a second power law. By comparing the floor and ceiling results, it is found that buoyancy has two opposite effects, one is enhancing the heat transfer to the surface by reducing the flame stand-off distance and the other reducing the chemical reaction completeness by intensifying the flame quenching at the wall. The overall buoyancy effect on the flame spread and mass burning processes depends on the flow condition.

I. INTRODUCTION

The study of the effects of flow velocity and turbulence, oxygen concentration, and orientation (ceiling or floor) on the spread of flames over a solid combustible surface is of practical interest because fires in corridors often spread over the ceiling or floor, and occur under vitiated conditions. The scarcity of information on these effects, and the potential utilization of the information in models of flame spread are the primary motivations for conducting this study. The experiments have yielded results that are potentially important not only in the modeling and prediction of flame spread in corridors, but also in other aspects of fire development and testing such as burning rates, flame lengths and combustion completeness.

A series of experiments has been performed to measure the ceiling flame spread rate over thermally thick PMMA sheets placed in gas flows with velocities ranging from 0.5 to 2.0 m/sec, turbulence intensities ranging from 0 to 20%, and oxygen mass fractions from 0.19 to 0.50. The effect of these flow parameters on the flame spread rate is complex and depends strongly on the interaction between the different parameters. Thus the interpretation of the results is difficult and laborious, and has taken a large portion of this year's program. The research progress made during the reporting grant period is presented below.

II. RESEARCH PROGRESS

EXPERIMENTAL APPARATUS

The experiments are conducted in the experimental apparatus shown schematically in Fig. 1. It consists of a small scale combustion wind tunnel and supporting instrumentation. The wind tunnel contains of three sections. A 0.89 m settling chamber/converging nozzle section, that directs oxidizer gas to the test section. A 0.61 m long test section with a rectangular cross section 0.122 m wide and 76 mm high. The side walls of the test section are made of 6.3 mm thick Pyrex glass for optical access. The floor and ceiling of the test section are made of 55 mm thick Marinite slabs. The fuel samples are mounted in the ceiling, or floor, flush in the Marinite walls. The fuel used in these experiments are 12.7 mm thick PMMA sheets (Rohm and Haas, Plexiglas G) 300 mm long by 70 mm wide. All the measurements presented in this work were conducted with the fuel specimen mounted in the ceiling wall.The PMMA sample is ignited at its upstream edge with an electrically heated Nichrom wire which initiates the spread of the flame over the whole width of the sample. The oxidizer gas flow is supplied to the test section from bottled Air, Nitrogen and Oxygen independently metered with critical nozzles, and mixed in the settling. Turbulence is introduced to the flow by means of perforated plates that are placed perpendicular to the flow at the exit of the converging nozzle. A prescribed turbulence intensity is obtained through a combination of flow velocity and plate blockage ratio. A description of the turbulence intensity distribution through the test section is given in Ref [1]. A 1.22 m long exhaust section is located after the test section and it contains several mixing plates to mix the exhaust gases and ensure uniform concentration distribution at the tunnel exaust. Exhaust gas samples are taken from the exit of the exhaust for species concentration and soot measurement.

The air flow velocity and turbulence intensity are measured with a one component LDV (TSI). Gas analyzers are used to measure the concentrations of major species O_2, CO, CO_2, NO (Horiba, Infrared) and unburned hydrocarbons (Horiba-flame ionization) in the exhaust gas flow. Soot concentration in the exhaust gas flow is also measured by collecting the soot with fiberfilm filter (Pallflex #T60A20) for a prescribed time period and subsequent filter weighting. An array of eight k-type, 0.13 mm diameter, thermocouples placed on the fuel surface at fixed locations along the centerline are used to measure the solid surface temperatures. An additional thermocouple located in the exhaust section after the mixing chamber is used to measure the exhaust gas temperature. A Schlieren system is also used to obtain qualitative information about the gas thermal layer.

The measured surface temperature histories are used to calculate the pyrolysis front location, flame spread rate, flame length and surface heat flux. The arrival of the pyrolysis front at the location of a particular thermocouple is considered to occur when the surface temperature reaches 390 ^oC[1]. The flame spread rate is calculated from the time interval needed for the pyrolysis front to travel the distance between two consecutive thermocouples. The calculated flame spread rates at the different thermocouple locations are then compared to determine if the flame accelerates or decelerates as it spreads along the solid surface. The flame length is calculated by determining the location of the thermocouple whose temperature is starting to rise at the moment that the pyrolysis front reaches a particular thermocouple. It should be noted that the calculated length is not necessarily the actual visible flame length, but the length of the solid surface with elevated temperature downstream from the pyrolysis front. For simplicity this length is called here the flame length. The surface heat flux is calculated from the solid surface temperature histories with the assumption that the solid fuel slab behaves as a semi-infinite medium exposed to a constant heat flux[1].

RESULTS AND DISCUSSION

Flame Spread Rate

The measured flame spread rates over PMMA sheets in a ceiling burning geometry are shown in Fig. 2 to 4, for oxygen mass fractions ranging from 0.19 to 0.50, and turbulence intensities from 0 (laminar) to 20%. The data are also presented graphically in a three dimensional diagram in Fig. 5 to facilitate the interpretation of the results. Within the length of the fuel samples, no consistent trend was observed on whether the spread rate increases or decreases along the sample length. Thus, the flame spread rate presented is an average of the values measured throughout the specimen length, and from three different tests. No data is presented for oxygen mass fractions lower than 0.19 because the flame spread could not be initiated or flame extinction occured after the flame had propagated for a short distance.

From Fig. 2 - 4, it is seen that at the higher flow velocities (U = 1.0 m/s, 2.0 m/s) the flame spread rate presents a maximum, and that the value of the turbulence intensity at which the maximum flame spread is observed shifts toward larger values as the velocity is decreased (from u'/U = 5 % at U = 2.0 m/s to u'/U = 15 % at U = 1.0 m/s). At a flow velocity of U = 0.5 m/s, the flame spread rate increases monotonically with the turbulence intensity, and no maximum point has been observed within our experimental conditions. A maximum may be present, however, at turbulence intensities beyond those that we can attain with our experimental apparatus. The flame spread rate increases monotonically with flow velocity, with the rate of increase dependent on the turbulence intensity and oxygen concentration. At higher oxygen concentration, the flame spread rate increases at a higher rate. The flame spread rate also increases monotonically with the oxygen concentration, with the rate of increase also dependent on the flow velocity and turbulence intensity. The rate of increase is larger at higher flow velocity. The dependence of the flame spread rate on the oxygen concentration shifts fron linear at low oxygen concentrations to quadratic at high oxygen concentrations.

In order to better understand the characteristics of the experimental results, it is convenient to briefly examine the mechanisms determing the spread of the flame. Previous experimental and theorectical work on the concurrent mode of flame spread indicate that heat transfer from the flame to solid fuel is the dominant mechanism in determining the rate of flame spread[2,3]. In fact, a simple energy analysis applied to a control volume in the unburnt solid downstream from the pyrolysis front provides an expression for the flame spread rate that seems to describe the spread process well. Assuming that the solid behaves as semi-infinite and the heat flux from the flame to the fuel surface, q_f, is constant throughout the downstream flame length, l_f, and that the solid pyrolyzes when its surface temperature reaches the pyrolysis temperature, T_p, the following expression is obtained for the spread rate of the pyrolysis front[4]

$$V_p = \frac{4\, q_f^2\, l_f}{\pi k \rho c\, (T_p - T_i)^2} \qquad (1)$$

where $k\rho c$ are the thermal properties of the solid and T_i the initial solid temperature. From Eq. (1) it is seen that the flow velocity, turbulence intensity and oxygen concentration affect flame spread rate primarily through their effect on the heat flux and the flame length. Thus, in order to understand the above flame spread results, it is important to determine how the flow velocity, turbulence and oxygen concentration affect the heat flux, q_f, and flame length l_f.

Flame Length

Previous studies on flame lengths[1,5,6,7,8], indicate that there is a power law correlation between the flame length, l_f, and the pyrolysis length, l_p, of the form

$$l_f = a\, l_p^{\,b} \qquad (2)$$

where a and b could be functions of the flow parameters. The present measurements show that, within our experimental conditions, the ratio between the flame length and the pyrolysis length, l_f/l_p is approximately constant along the specimen. The exponent b is found to be weakly dependent on the flow parameters, but close to unity. Thus, the data will be presented in terms of the flame to pyrolysis lengths ratio. Average values of l_f/l_p as a function of the flow turbulence intensity for several values of the oxygen concentration are presented in Fig. 6-8 for the flow velocities tested. A three dimensional graph is presented in Fig. 9. The results of Fig. 6-9 show that, as a general trend, the ratio of flame to pyrolysis lengths increase as the flow velocity and oxygen concentration increase. As per the dependence on the turbulence intensity, it is seen that, as with the spread rate, at the higher flow velocities (U = 1.0 m/s, 2 m/s) the flame length to pyrolysi length ratio presents a maximum, and that the value of the turbulence intensity at which the maximum is observed shifts toward larger values as the velocity is decreased (from u'/U = 5 % at U = 2.0 m/s to u'/U = 15 % at U = 1.0 m/s). At a flow velocity of U = 0.5 m/s, the l_f/l_p increases monotonically with the turbulence intensity, and no maximum point has been observed within our experimental conditions. Here also it can be speculated that although the maximum is not observed in the range of turbulence intensities tested, it may occur at higher turbulence levels.

The effects of the flow velocity and oxygen concentration are primarily the result of the increase in the surface heat flux, and consequently of the fuel pyrolysis rate. In the former case this is due to the reduction of the flame stand off distance[1,9], and in the latter to the increase in the fuel temperature. In the case of the turbulence intensity, there are two opposing factors that determine the observed trends. Turbulence enhances fuel and oxidizer mixing, which in turn produces a stronger, more complete reaction and a larger heat release (this is justified further below). A stronger reaction means a faster consumption of reactants, and consequently a shorter flame. However, the larger heat release results in an increase of the surface heat flux, and consequently of the mass burning rate[1,10] which in turn produces a longer flame length. Thus, the flame length is determined by the interaction between these two effects, and the final increase or decrease will depend on which of the above two factors is dominant.

Surface Heat Flux

Previous experimental studies of the problem[1,8,11], and boundary layer analyses of the problem[2], suggest a dependence between the heat flux and the pyrolysis length of the form :

$$q_f^2 l_p^{\,c} = \mathrm{d} \tag{3}$$

where c and d may depend on the flow parameters. In the present experiments, the product $q_f^2 l_p$ has been found to be approximately constant along the surface, in qualitative agreement with forced flow boundary layer heat transfer predictions[2], with c weakly dependent on flow properties but close to unity. Thus the data is presented in terms of this product. The average value of $q_f^2 l_p$

has been plotted as a function of the turbulence intensity for several values of oxygen concentration in Fig. 10. A three dimensional graph is presented in Fig. 11. It is seen that the heat flux/ pyrolysis length product increases with flow velocity, turbulence intensity and oxygen concentration.

These results can be explained qualitativelly in terms of boundary layer diffusion flame analysis. The heat flux q_f from the flame to the fuel surface can be modeled approximately as :

$$q = (K + K_T) \frac{T_f - T_p}{\delta} + q_r \tag{4}$$

where K is the heat transfer coefficient for laminar flow and K_T is the contribution from turbulence intensity (eddy diffusivity), T_f is the flame temperature, δ is the thermal boundary layer thickness, and q_r is the thermal radiation. From Eq. (4) it is seen that increasing the flow velocity increases the surface heat flux through the reduction of the thermal boundary layer thickness and consequently of the flame stand-off distance[1,9]. Considering only convection, boundary layer analysis predicts a square root dependence of the boundary layer thickness with the flow velocity, and thus of the heat flux on the flow velocity. Thus, according to Eq. (4), d should be linearly proportional to the flow velocity, which is in agreement with our experimental data. Oxygen concentration increases the heat transfer from the flame to the solid fuel by increasing the flame temperature and the formation of soot (see below). Thus, according to Eq. (3), d should have a square power dependence on oxygen concentration. Our results show a linear dependence at low oxygen concentrations and low flow velocity, which shifts toward a square power dependence at high oxygen concentrations. As it is shown below, we attribute this result to the incompleteness of combustion that occurs at low oxygen concentrations and low velocity. Under incomplete combustion the linear relationship between flame temperature and oxygen concentration breaks down and so does the square power dependence predicted by Eq. (3). Flow turbulence increases the surface heat flux due to turbulent eddy diffusivity effects[12], and also by the increase in the flame temperature through the enhanced mixing effect (see Fig. 16).

The flame radiation term plays a secondary role in our study mainly because of the small size of the specimen. However, if the specimen size is large enough, it has been shown that thermal radiation plays a dominant heat transfer mode in the flame spread process[13] and the thermal radiation term cannot be neglected. Soot is the major cause for thermal radiation heat transfer in a combustion process and the effect can be seen on the heat flux term $q_f^2 l_p$ as shown in Fig. 10 - 11. At high flow velocity, soot content decreases with turbulence intensity. This reduces the thermal radiation heat transfer and leads to a smaller increase rate of the heat flux term as turbulence goes up. Soot formation also helps in bringing the heat flux term to a very high value as the oxygen concentration increases.

Exhaust Gases Species and Soot Concentrations, and Temperature

Species concentrations

Further information and verification about the mechanisms controlling the flame spread process are obtained by analyzing the concentrations of major species in the exhaust gas flow. A good indication of combustion completeness is the carbon monoxide (CO) and unburnt hydrocarbons (HC) concentrations. The variation of CO and HC with oxygen mass fraction at different turbulence intensities are shown in Fig. 12 and 13 respectively. Three dimensional plots are presented in Fig. 14 and 15. From the figures it is seen that the amount of CO and HC decrease as the flow velocity, turbulence intensity and oxygen concentration are increased. It indicates that the combustion becomes more complete as the value of these three flow parameters are increased. The observation that the highest CO and HC concentrations occur for low values of the oxygen concentration and flow velocity is particularly important from a fire safety point of view since these are conditions that are often encounterd in fires.

Exhaust temperature

Additional information about the effect of the flow parameters on the combustion completeness is obtained from the measurements of the exhaust gas temperature presented in Fig. 16. The results show that the exhaust gas temperature increases with flow velocity, turbulence intensity and oxygen concentration. Since the exhaust gas temperature is related to the rate of heat release, these results further support that an increase in any of the three flow parameters enhances combustion completeness. The increase in heat release rate is also reflected in the surface heat flux. Naturally, oxygen concentration has the strongest effect on the flame temperature and heat flux.

Soot formation

Another important source of information is the measurements of the effect of flow parameters on soot formation. A three-dimensional plot showing the variation of soot content with oxygen concentration and turbulence intensity, at flow velocities of $U = 2.0$ m/s and $U = 0.5$ m/s is shown in Fig. 17. It is seen that the largest amount of soot is formed at low flow velocity ($U = 0.5$ m/s), and high oxygen concentrations and flow turbulence. At higher flow velocities ($U = 1.0$ m/s and 2.0 m/s), however, soot formation decreases as the turbulence intensity increases. This latter result is in general agreement with previous of soot formation in gas jets. Turbulence reduces soot formation because the resulting vigorous reaction favors soot oxidation, which counteracts the increase in pyrolyzed fuel. The increase in soot formation as the oxygen concentration increases seems to be primarily the result of the increase in fuel pyrolysis, which apparently cannot be totally oxidized in spite of the resulting vigorous reaction. Finally, as explained below, the results at low flow velocity seem to be caused primarily by effects related to fuel sedimentation near the wall due to buoyancy pushing the hot gases upward against the ceiling.

The Effect of Buoyancy

Most of the observed changes in the trends of the different problem parameters as the flow velocity is decreased, can be attributed to the effect of buoyancy on the ceiling thermal boundary layer. In ceiling burning, buoyancy pushes the hot postcombustion gases toward the fuel surface and induces a stratification and stabilization of the ceiling thermal layer. Theoretically, the effects are more pronounced at low forced flow velocities, and if the velocity is large enough the effects would be negligible. However this last limit cannot be reached before blowing off the flame[1]. Since buoyancy decreases the boundary layer thickness, and consequently the flame stand off distance, it increases the surface heat flux, and through it the fuel pyrolysis rate. At the same time, the stratification of the thermal layer hampers the entrainment of oxidizer into the reaction zone, which together with the increase in fuel pyrolysis produces fuel rich condtion and consequently a weakened reaction[1,8]. These last effect is clearly reflected in the larger concentrations of the carbon monoxide and unburned hydrocarbons observed at low flow velocity, turbulence intensity and oxygen concentrations (Figs. 12 - 15). For the other parameters fixed, increasing the turbulence intensity reduces significantly the CO and HC concentrations, indicating that turbulence favors air entrainment and results in a more vigorous reaction. Similar result is observed by increasing the oxygen concentration. Buoyancy is also reflected in the amount of soot formed at low flow velocity and high oxygen concentration (Fig.17). At low flow velocity, the soot just remains inside the thermal layer and is not oxidised. It also appears that turbulence brings the soot even closer to the wall and that the relatively cold temperature of the wall quenches the soot oxidation process. In our experiments we could observe a very thick layer of soot deposited on the PMMA surface at low flow velocity and especially when the turbulence intensity was very high.

Thus, although buoyancy enhances the surface heat flux by reducing the flame stand off distance, it also hampers it by reducing the rate of heat release (flame temperature). Furthermore, a smaller air entrainment and larger pyrolysis rate produces a larger flame length. Since both parameters affect the flame spread rate, whether buoyancy will enhance or deter the flame spread rate depends on which one of the above effects is dominant. From the results of Fig. 2 it is seen that at low velocity, increasing turbulence results in an increase of the spread rate due to the combined effect of a higher heat release rate and surface heat flux and slightly longer flame due to the enhancement of the reaction. As the flow velocity is increased, the effect of fuel stratification becomes less important, and the reduction in flame length due to the stronger reaction as the turbulence intensity is increased becomes dominant over the increase in the heat flux, resulting in a decrease of the flame spread rate at large turbulence intensities.

Data Correlation

The flame spread data of Fig. 2, together with the flame length and surface heat flux data of Fig. 6, 7, 8 and 10 can be used to verify the validity of Eq. (1). This is done by plotting the non-dimensional flame spread rate $V = \pi V_p k\rho c(T_p - T_i)^2/4(q_f^2 l_p)(l_f/l_p)$ as a function of the oxygen mass fraction, at different flow velocity, and turbulence intensity, as shown in Fig. 18. The values of the properties used in the calculations are T_p = 390 °C, k = 1.99 x 10^{-2} J/smK, ρ = 1190 kg/m^3 and c = 1.46 kJ/kgK. It is seen that Eq. (1) describes the concurrent flame spread process very well, particularly considering the variety of conditions at which the data was taken.

III PUBLICATIONS AND PRESENTATIONS

The following publications and presentations have been made during this reporting period :

1. Zhou, L., and Fernandez-Pello, A.C., Twenty-Fourth Symposium (International) on Combustion, p. 1721-1728, The Combustion Institute, Pittsburgh, 1992.

2. Zhou, L., and Fernandez-Pello, A.C., Comb Flame, 92, 45-59, 1993.

3. Chao, Y.H. and Fernandez-Pello, A.C. "Flame Spread in a Vitiated Concurrent Flow" Accepted for presentation at the Minisymposium on Heat and Mass Transfer in Fire and Combustion, 1992 ASME/AIChE National Heat Transfer Conference, San Diego, CA. August 1992.

4. Chao, Y.H. and Fernandez-Pello, A.C. "Turbulent Concurrent Flame Spread : Effect of Oxygen Concentration" Western State Section/The Combustion Institute, 1993 Spring Meeting, University of Utah, Salt Lake City, Utah.

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9. Chao, Y.H., and Fernandez-Pello, A.C., "Flame Spread in a vitiated Concurrent Flow", 28th National Heat Transfer Conference, San Diego, CA, 1992.
10. Zhou, L., and Fernandez-Pello, A.C., Twenty-Fourth Symposium (International) on Combustion, p. 1721-1728, The Combustion Institute, Pittsburgh, 1992.
11. Zhou, L., and Fernandez-Pello, A.C., Twenty-Fourth Symposium (International) on Combustion, p. 1709-1714, The Combustion Institute, Pittsburgh, 1990.

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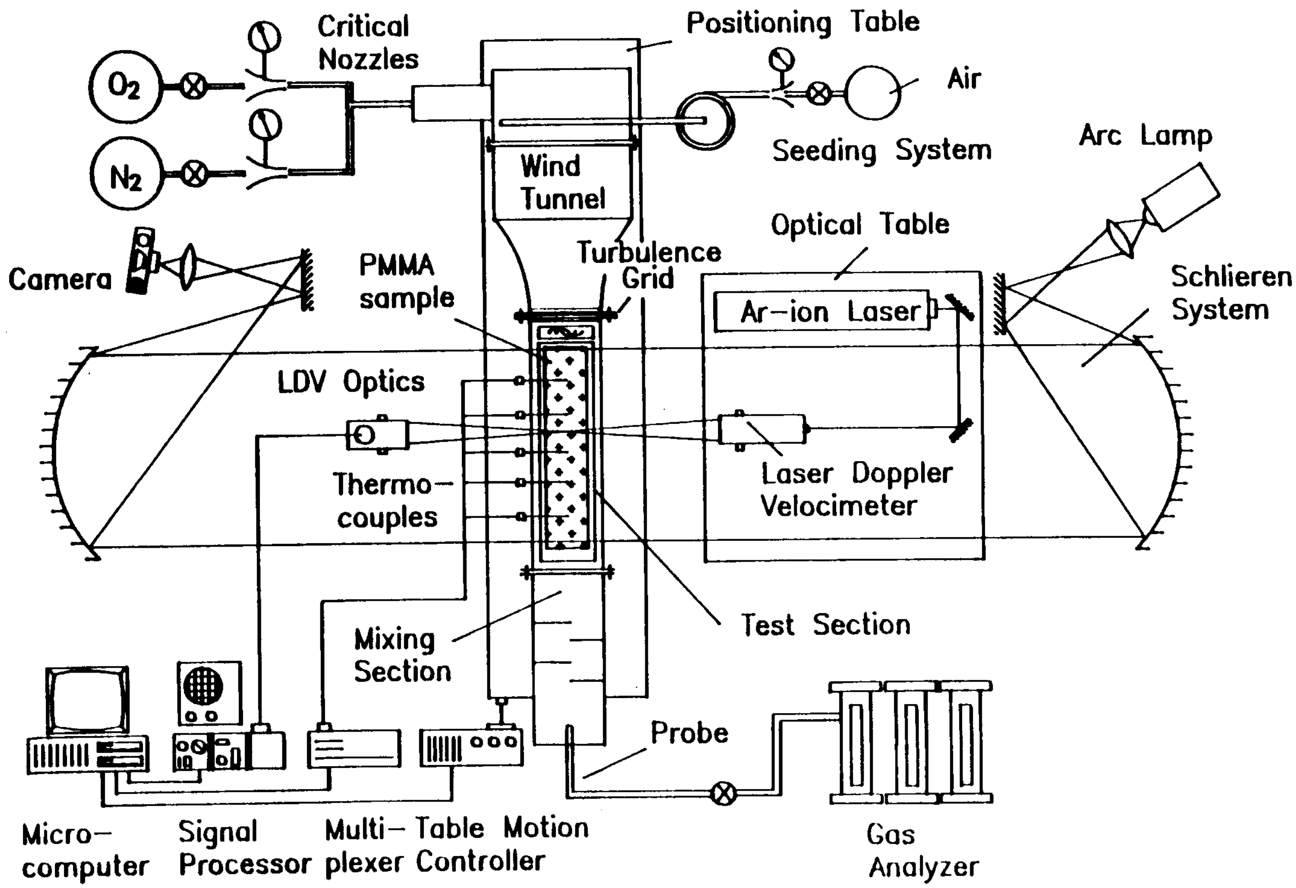
LIST OF FIGURES



O_2
N_2
Critical Nozzles
Positioning Table
Air
Seeding System
Arc Lamp
Wind Tunnel
Optical Table
Turbulence Grid
Camera
PMMA sample
Schlieren System
Ar-ion Laser
LDV Optics
Laser Doppler Velocimeter
Thermo-couples
Mixing Section
Test Section
Probe
Micro-computer
Signal Processor
Multi-plexer
Table Motion Controller
Gas Analyzer

Fig. 1

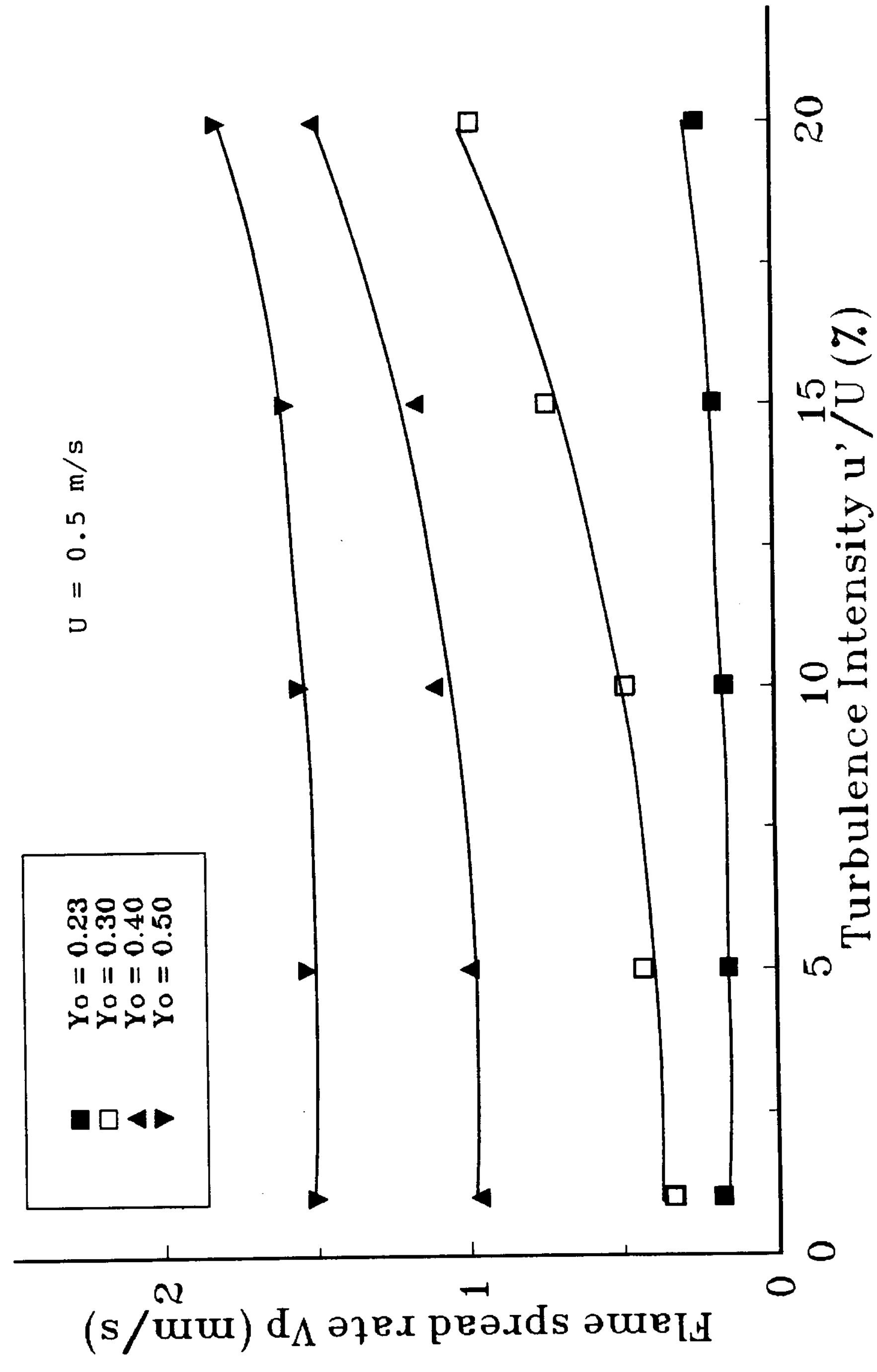
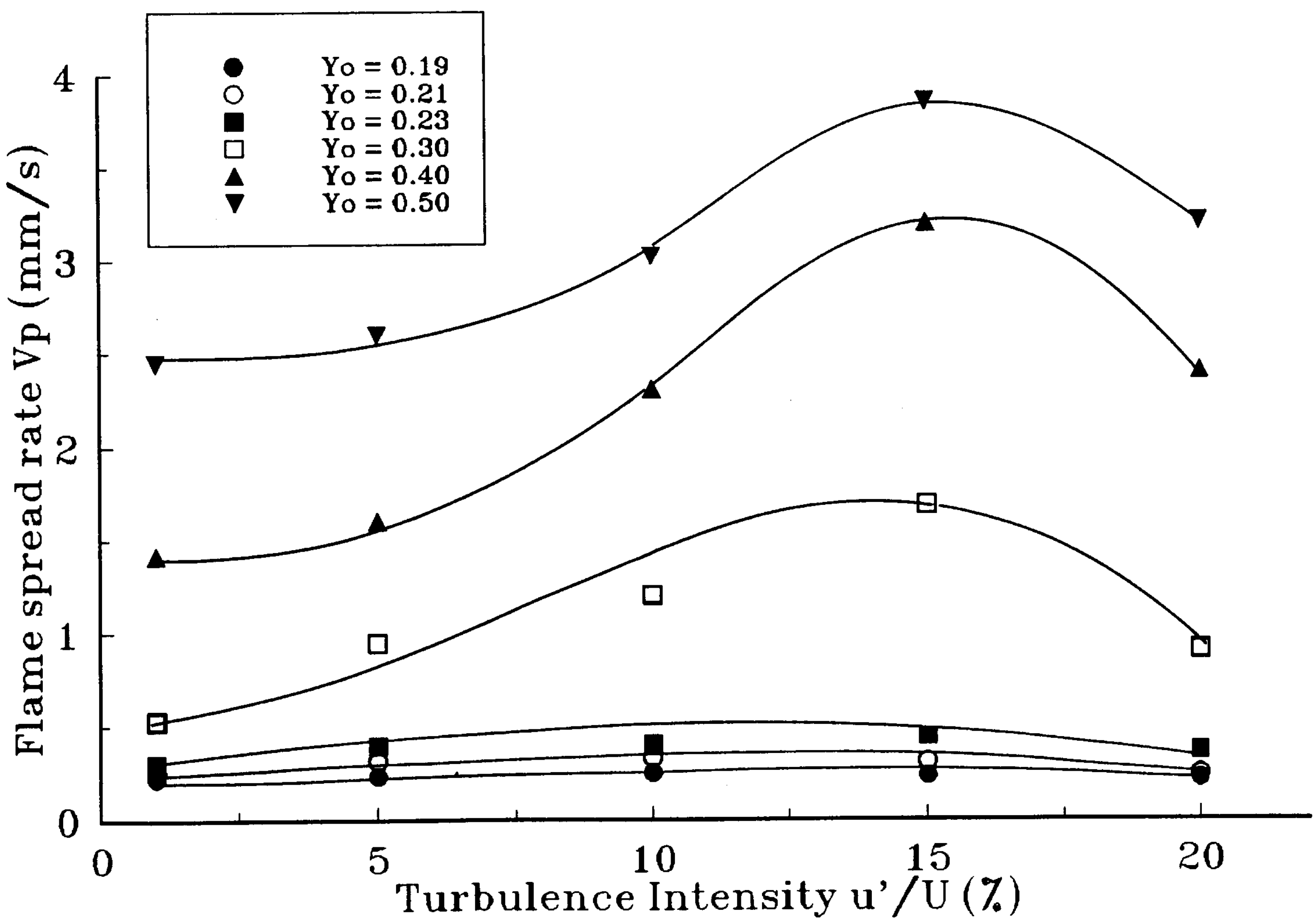

U = 0.5 m/s
Yo = 0.23
Yo = 0.30
Yo = 0.40
Yo = 0.50
Flame spread rate Vp (mm/s)
Turbulence Intensity u'/U (%)
0
1
2
0
5
10
15
20

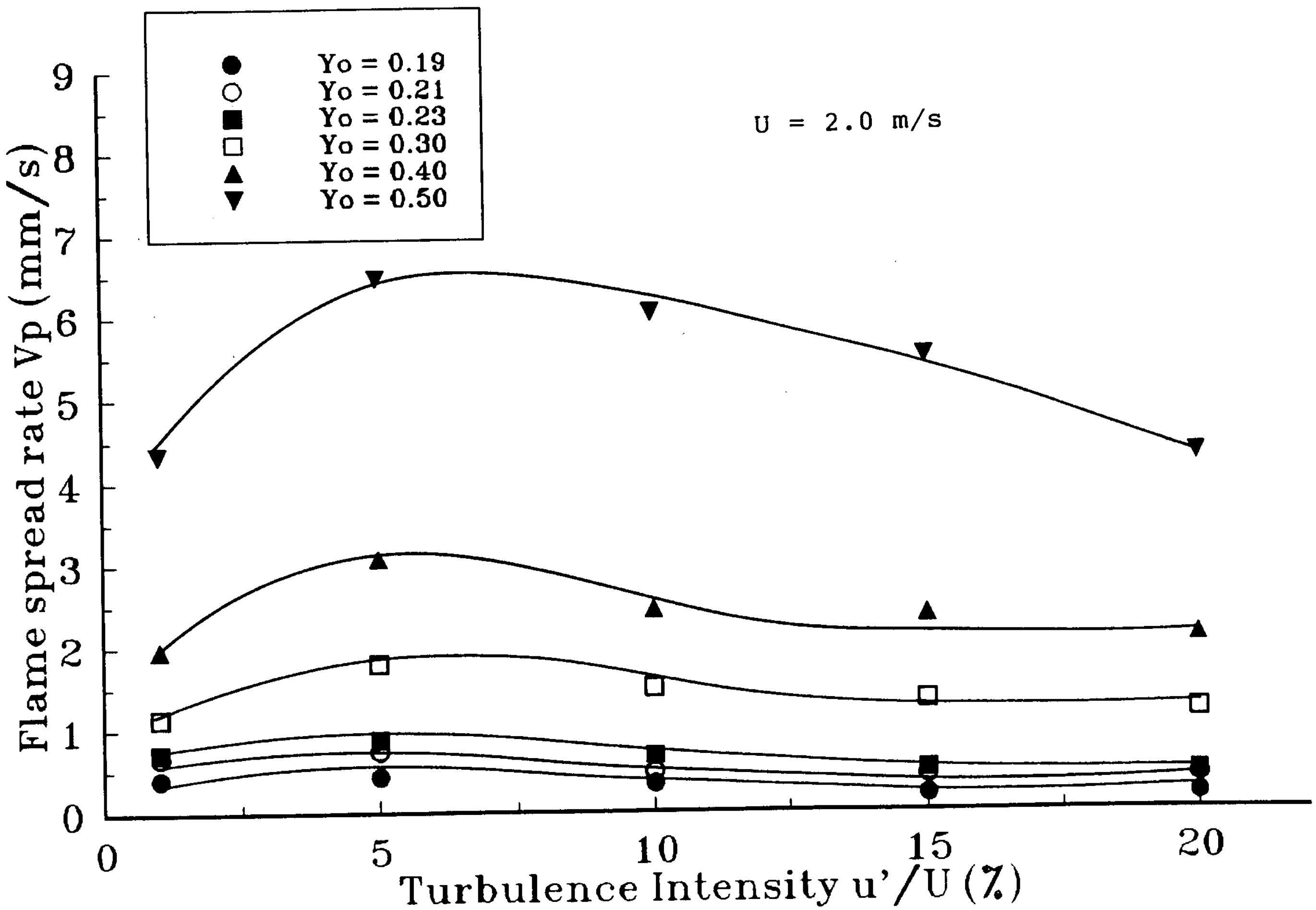
Fig. 2

U = 1.0 m/s



Yo = 0.19
Yo = 0.21
Yo = 0.23
Yo = 0.30
Yo = 0.40
Yo = 0.50
Flame spread rate Vp (mm/s)
0
1
2
3
4
0
5
10
15
20
Turbulence Intensity u'/U (%)

Fig. 3



Yo = 0.19
Yo = 0.21
Yo = 0.23
Yo = 0.30
Yo = 0.40
Yo = 0.50
U = 2.0 m/s
Flame spread rate Vp (mm/s)
Turbulence Intensity u'/U (%)
0
1
2
3
4
5
6
7
8
9
0
5
10
15
20

Fig. 4

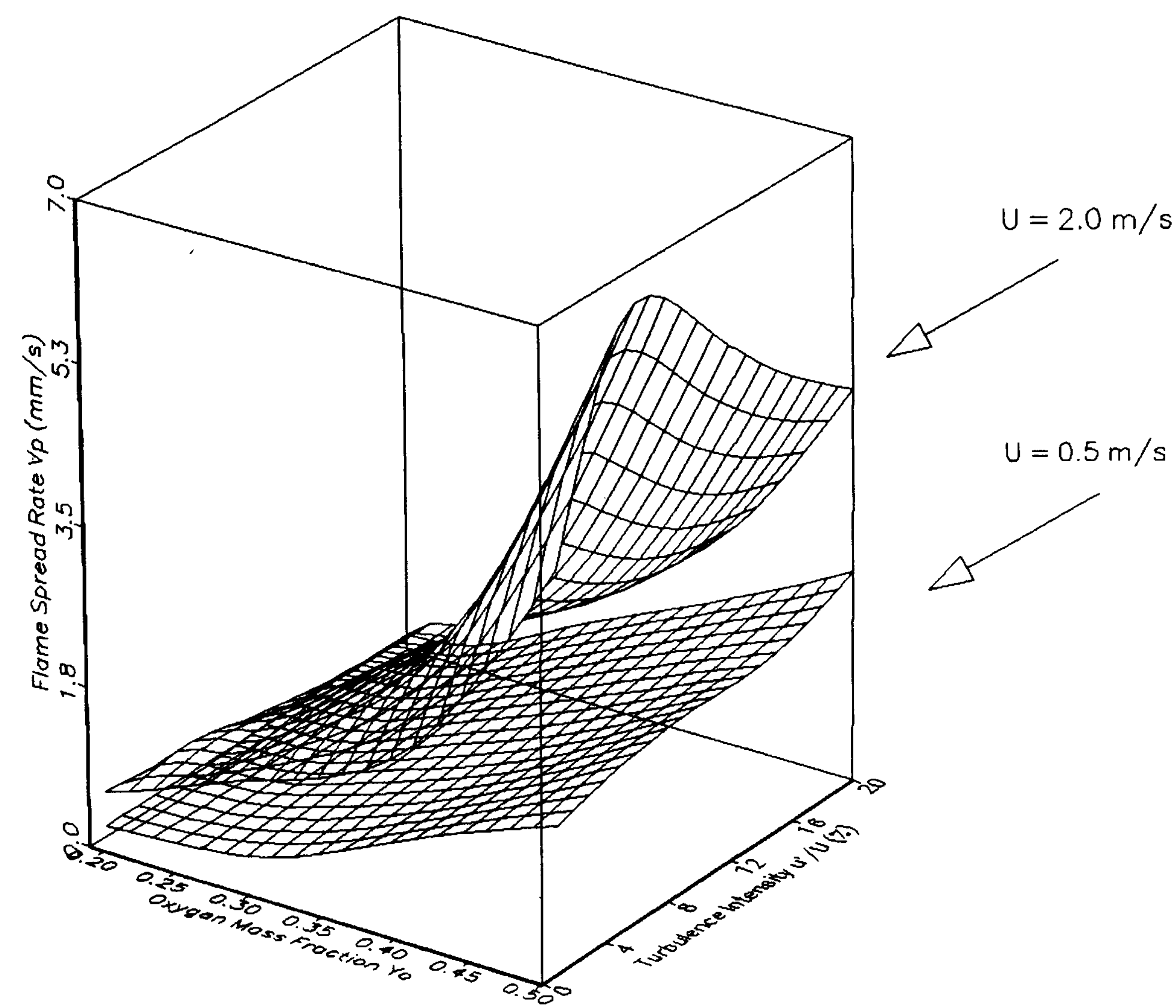

Flame Spread Rate Vp (mm/s)
7.0
5.3
3.5
1.8
0.0
0.20
0.25
0.30
0.35
0.40
0.45
0.50
Oxygen Mass Fraction Yo
0
4
8
12
16
20
Turbulence Intensity u'/U (%)
U = 2.0 m/s
U = 0.5 m/s

Fig. 5

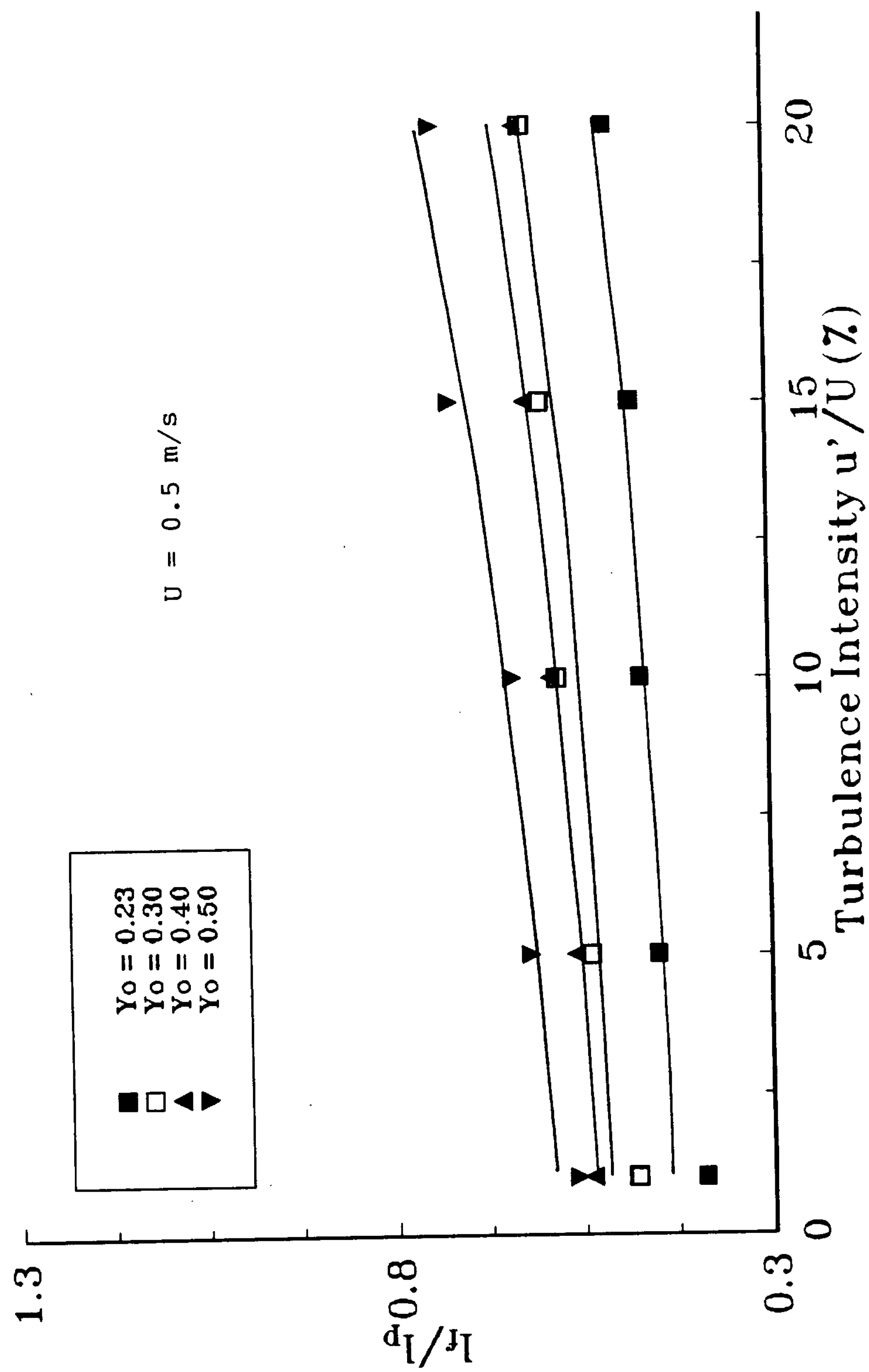
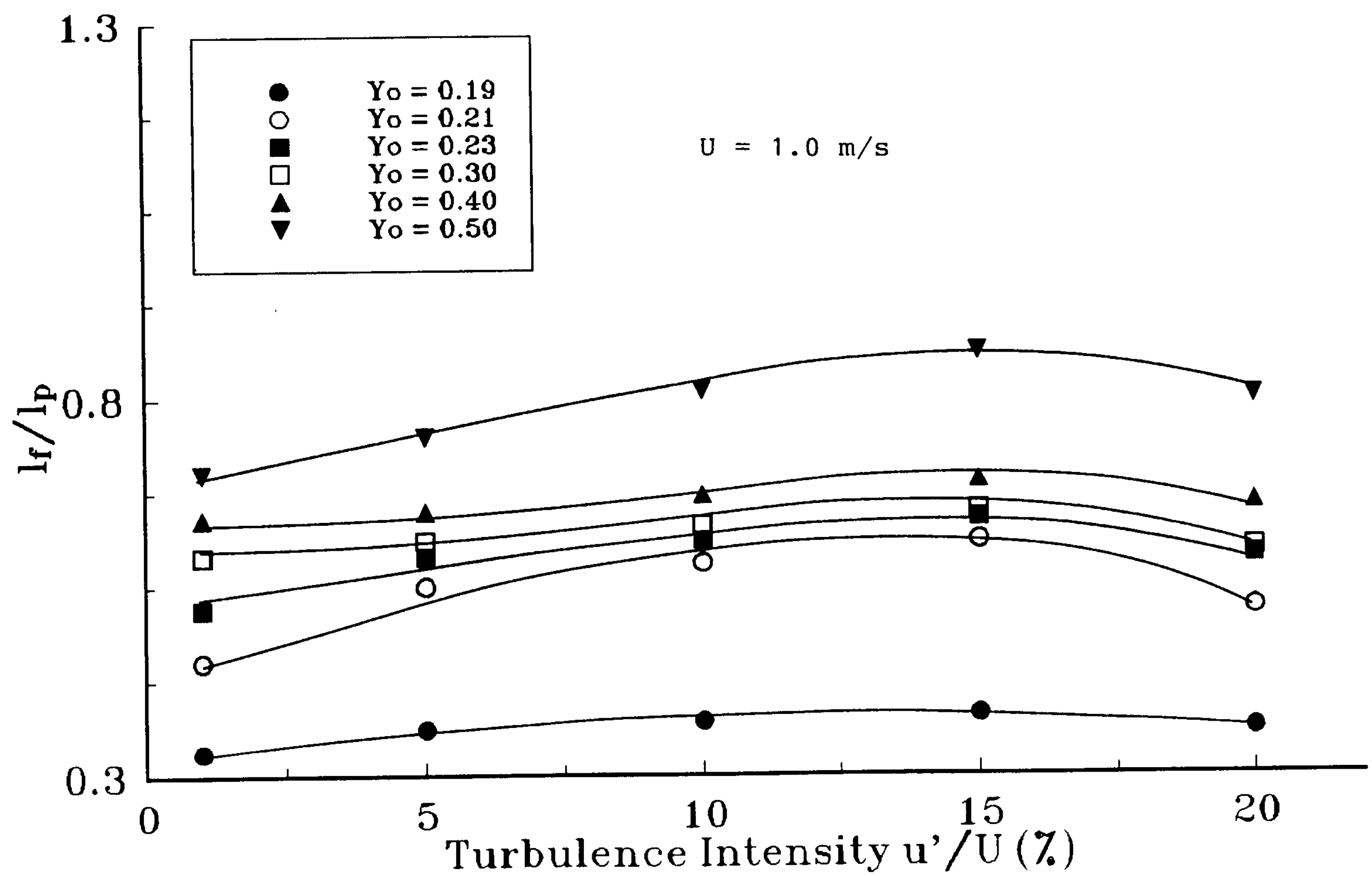
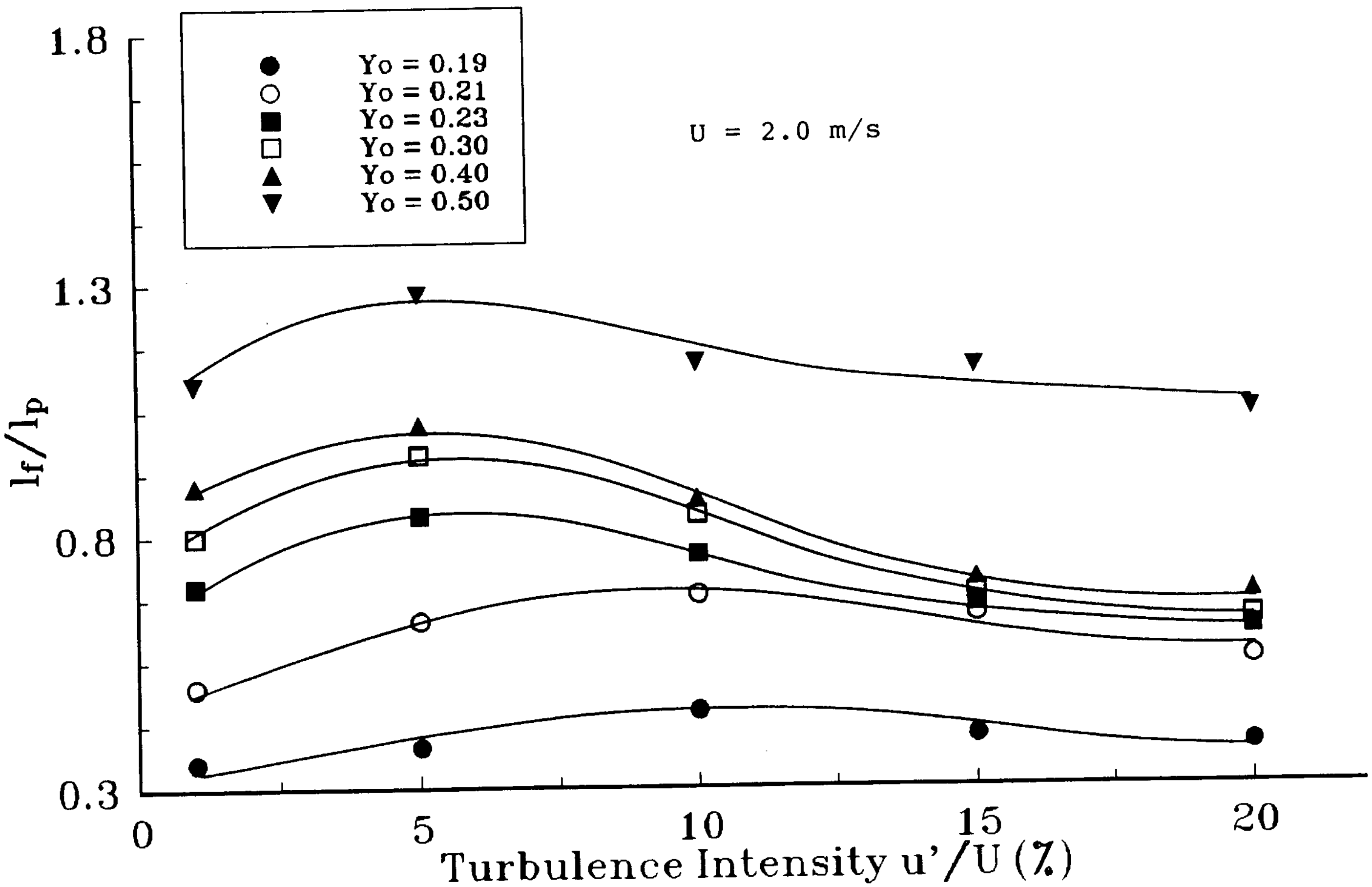

U = 0.5 m/s
Yo = 0.23
Yo = 0.30
Yo = 0.40
Yo = 0.50
1.3
0.8
0.3
l_f/l_p
0
5
10
15
20
Turbulence Intensity u'/U (%)

Fig. 6



1.3
0.8
0.3
l_f/l_p
0
5
10
15
20
Turbulence Intensity u'/U (%)
Yo = 0.19
Yo = 0.21
Yo = 0.23
Yo = 0.30
Yo = 0.40
Yo = 0.50
U = 1.0 m/s

Fig. 7



Yo = 0.19
Yo = 0.21
Yo = 0.23
Yo = 0.30
Yo = 0.40
Yo = 0.50
U = 2.0 m/s
1.8
1.3
0.8
0.3
l_f/l_p
0
5
10
15
20
Turbulence Intensity u'/U (%)

Fig. 8

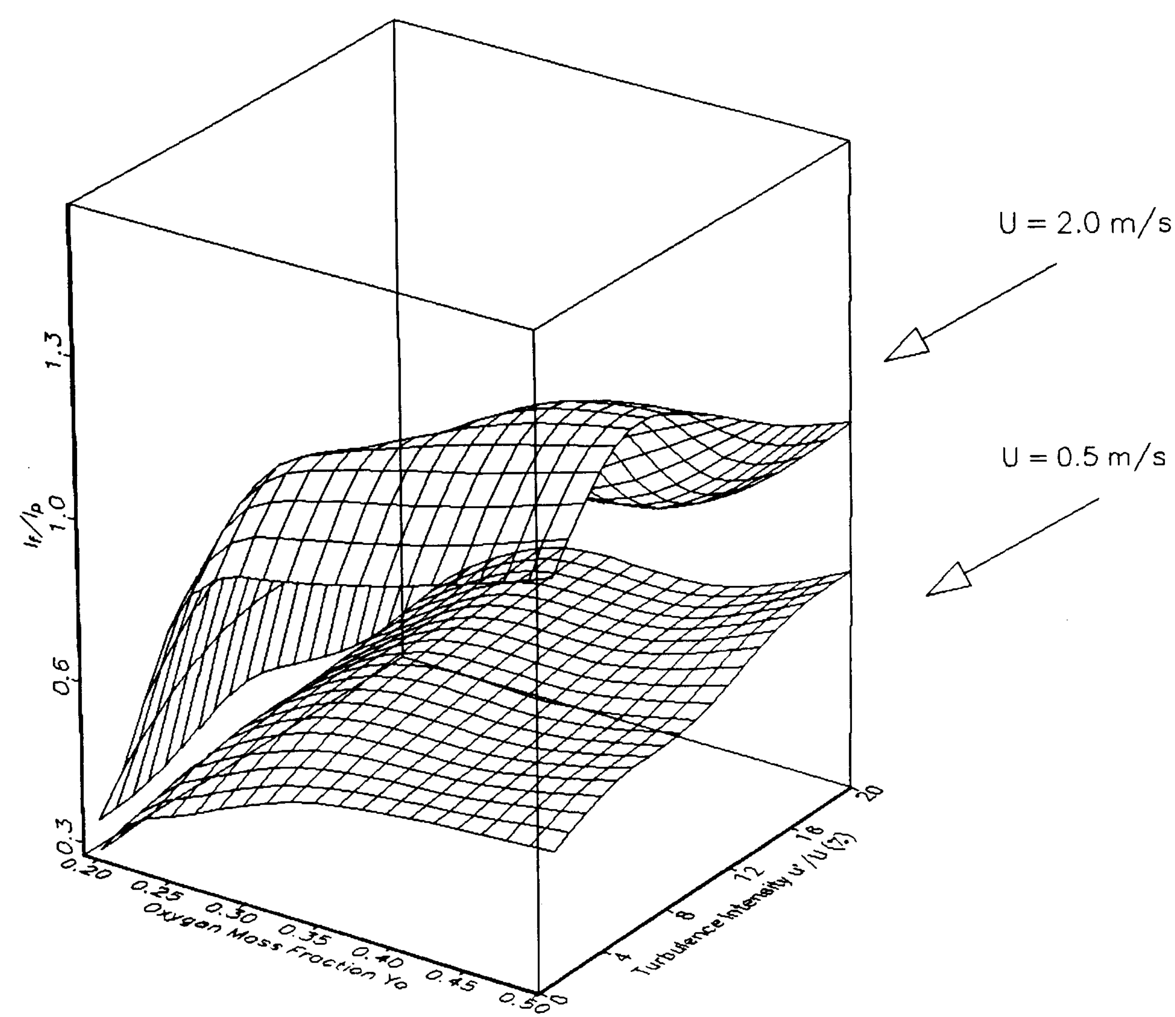
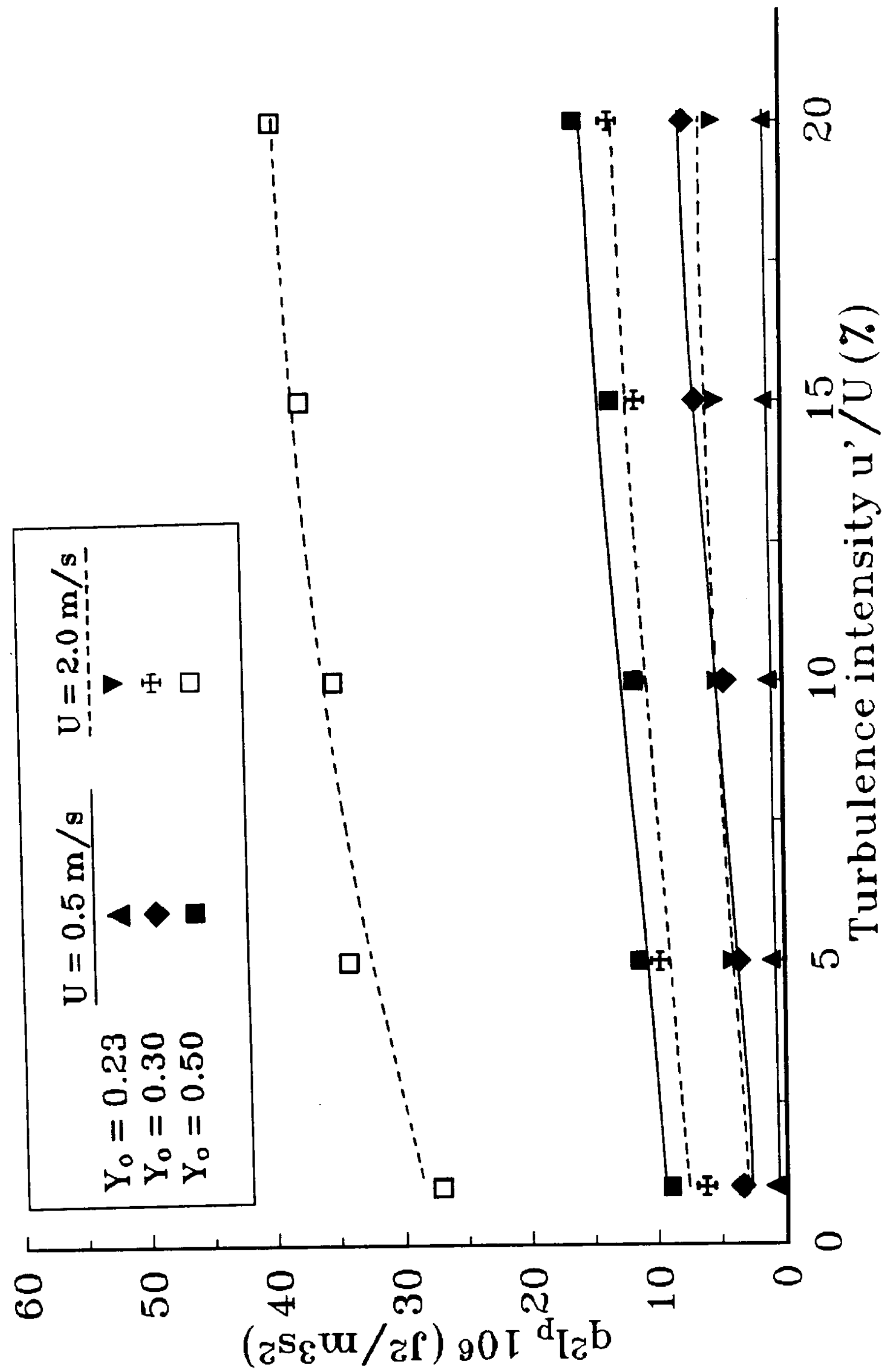

U = 2.0 m/s
U = 0.5 m/s
l_f/l_p
0.3
0.6
1.0
1.3
0.20 0.25 0.30 0.35 0.40 0.45 0.50
Oxygen Mass Fraction Yo
0 4 8 12 16 20
Turbulence Intensity u'/U (%)

Fig. 9



$Y_o = 0.23$
$Y_o = 0.30$
$Y_o = 0.50$
U = 0.5 m/s
U = 2.0 m/s
$q^2 l_p\ 10^6\ (J^2/m^3s^2)$
0
10
20
30
40
50
60
0
5
10
15
20
Turbulence intensity u'/U (%)

Fig. 10

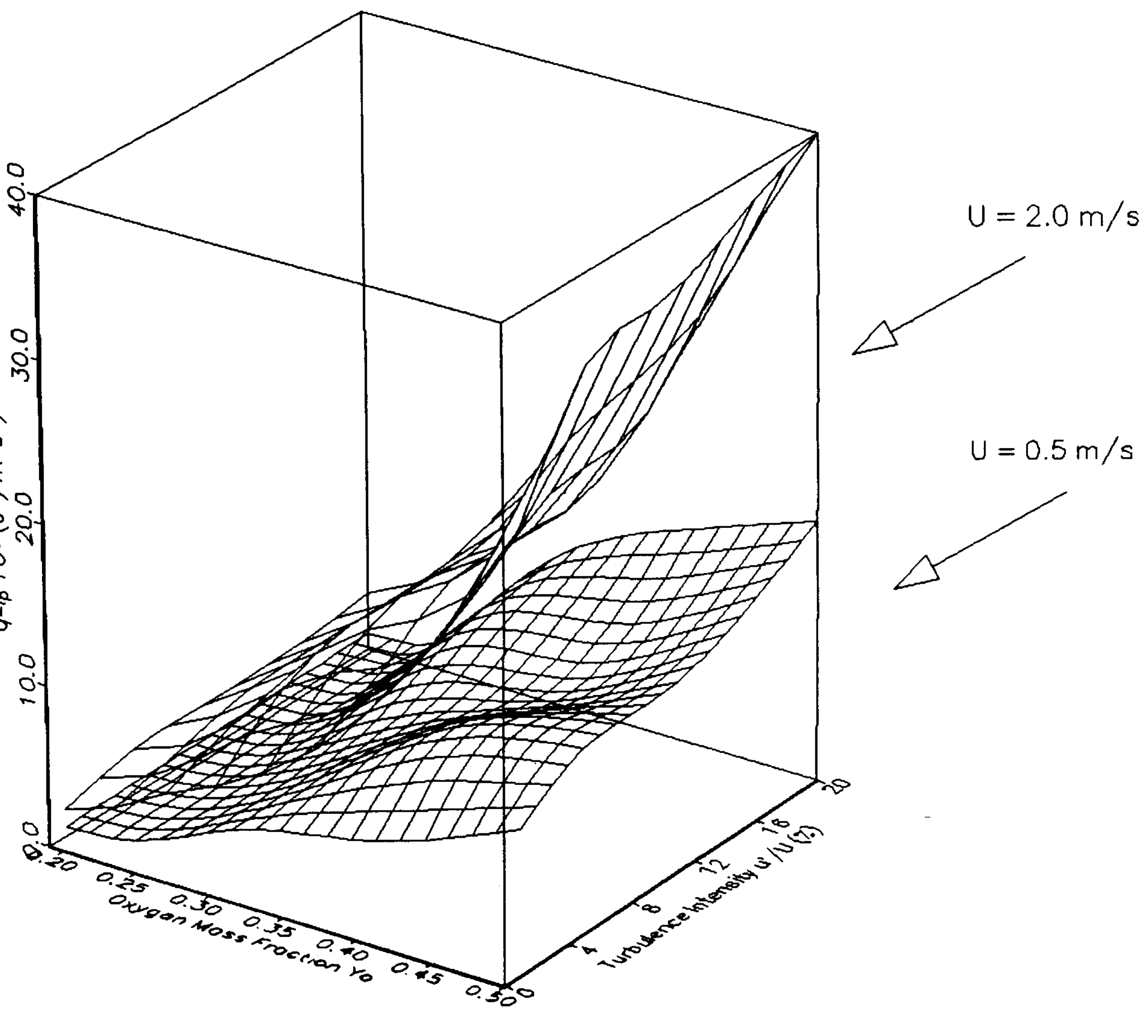
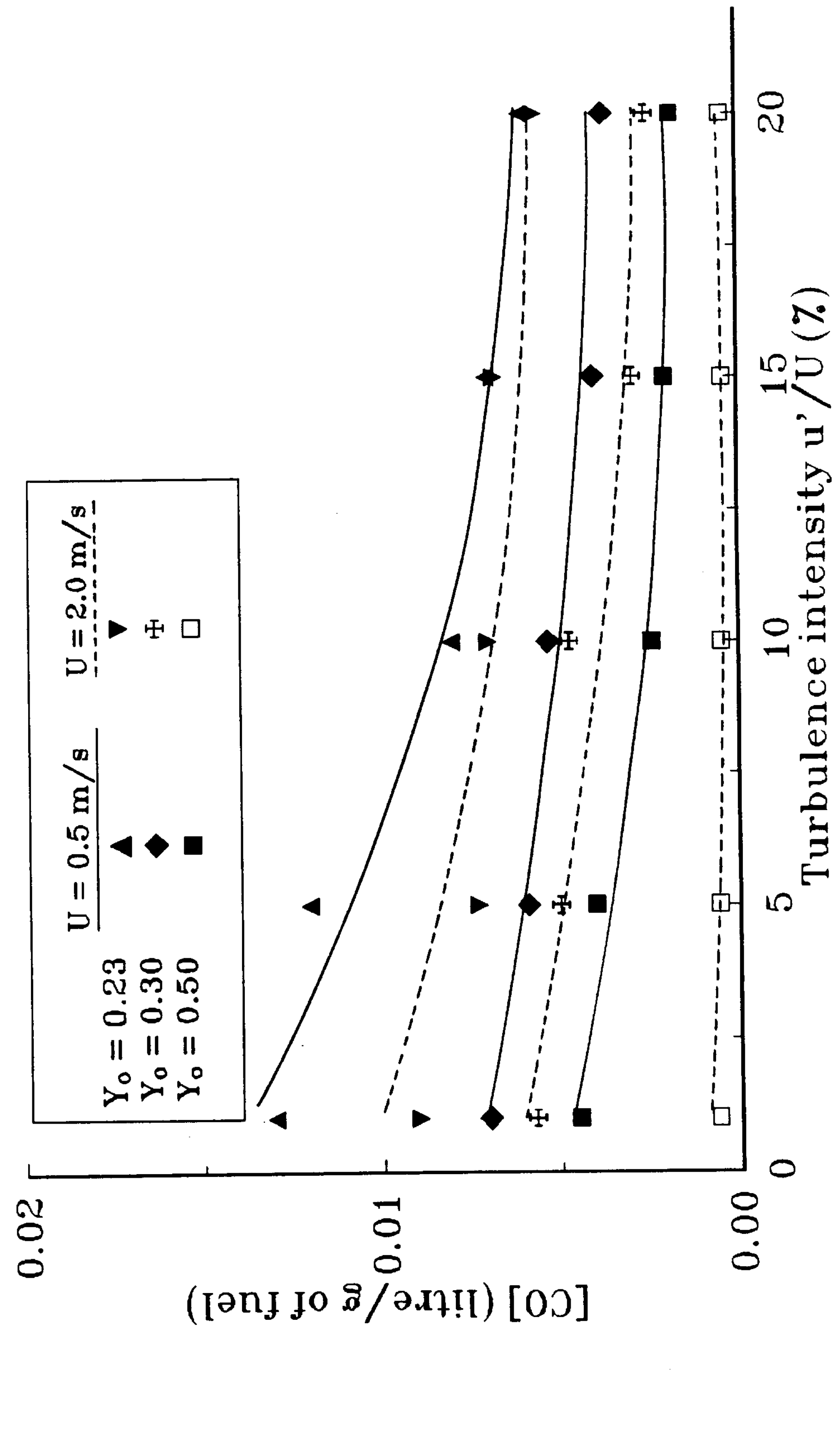

U = 2.0 m/s
U = 0.5 m/s
40.0
30.0
20.0
10.0
0.0
q2lp 106 (J2/m3s2)
0.20
0.25
0.30
0.35
0.40
0.45
0.50
Oxygen Mass Fraction Yo
0
4
8
12
16
20
Turbulence Intensity u'/U (%)

Fig. 11



[CO] (litre/g of fuel)
0.02
0.01
0.00
0
5
10
15
20
Turbulence intensity u'/U (%)
U = 0.5 m/s
U = 2.0 m/s
Y_o = 0.23
Y_o = 0.30
Y_o = 0.50

Fig. 12

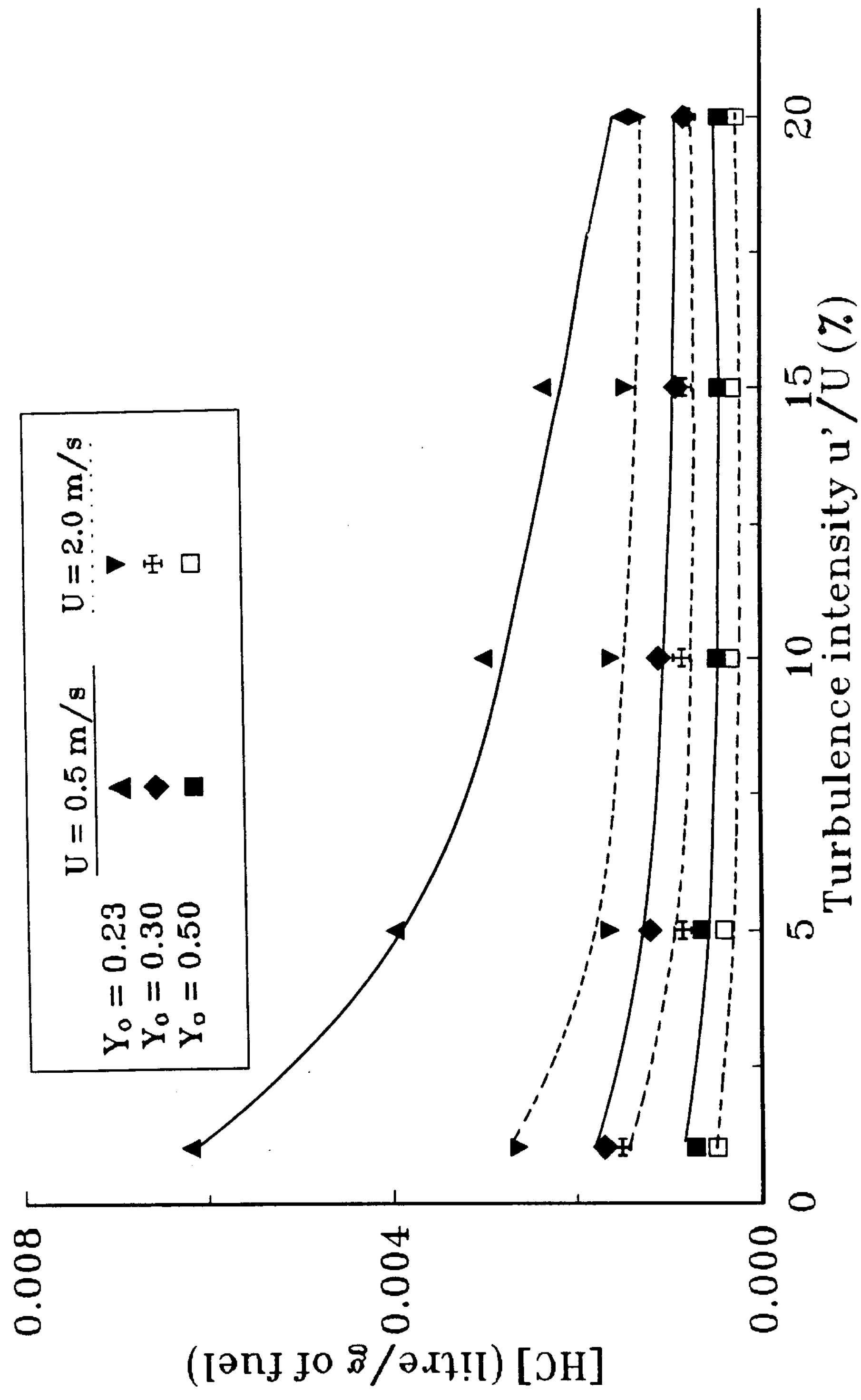

[HC] (litre/g of fuel)
0.008
0.004
0.000
0
5
10
15
20
Turbulence intensity u'/U (%)
$Y_o = 0.23$
$Y_o = 0.30$
$Y_o = 0.50$
U = 0.5 m/s
U = 2.0 m/s

Fig. 13

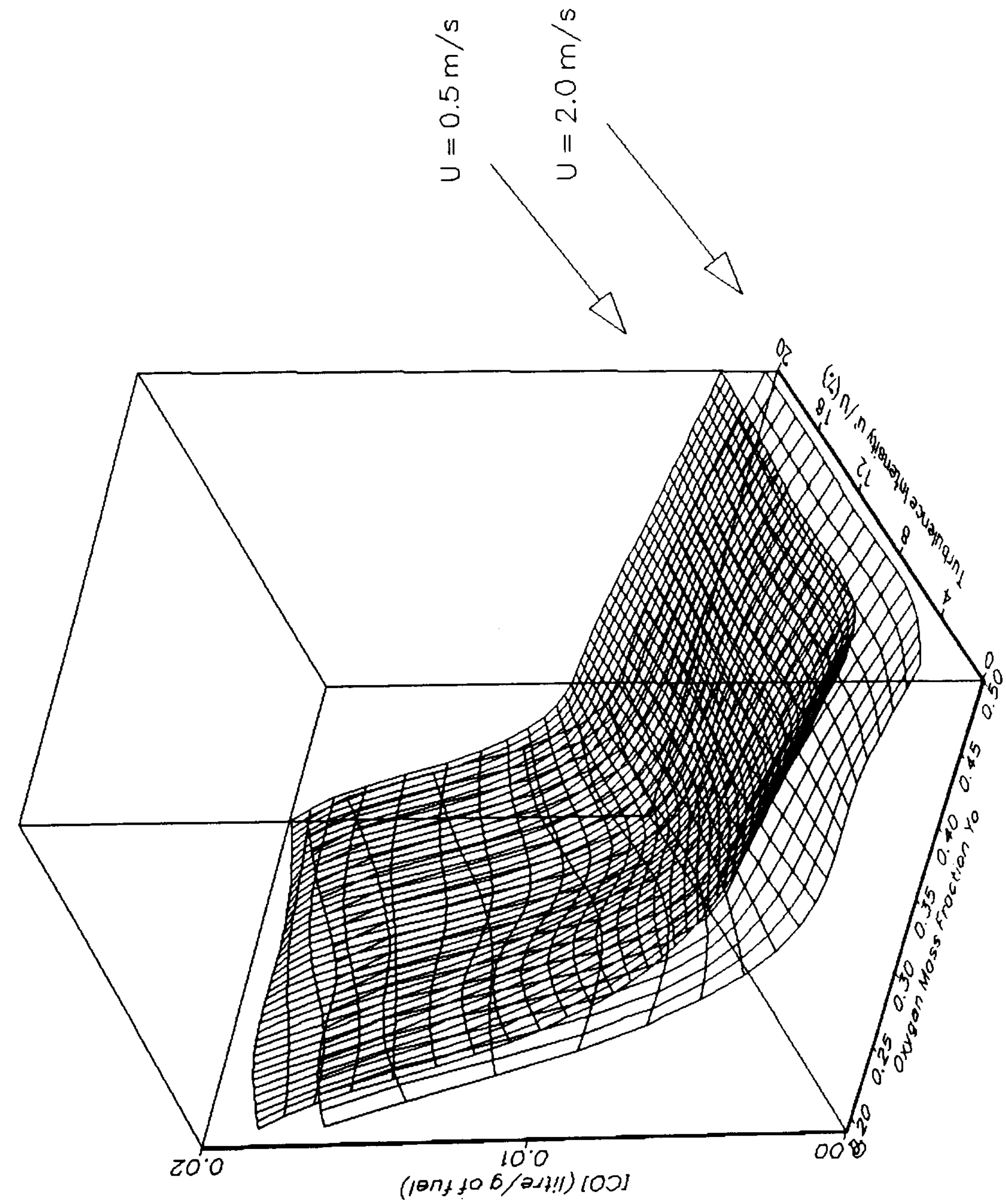

U = 0.5 m/s
U = 2.0 m/s
[CO] (litre/g of fuel)
0.00
0.01
0.02
Oxygen Mass Fraction Yo
0.20
0.25
0.30
0.35
0.40
0.45
0.50
Turbulence intensity u'/U (%)
0
4
8
12
16
20

Fig. 14

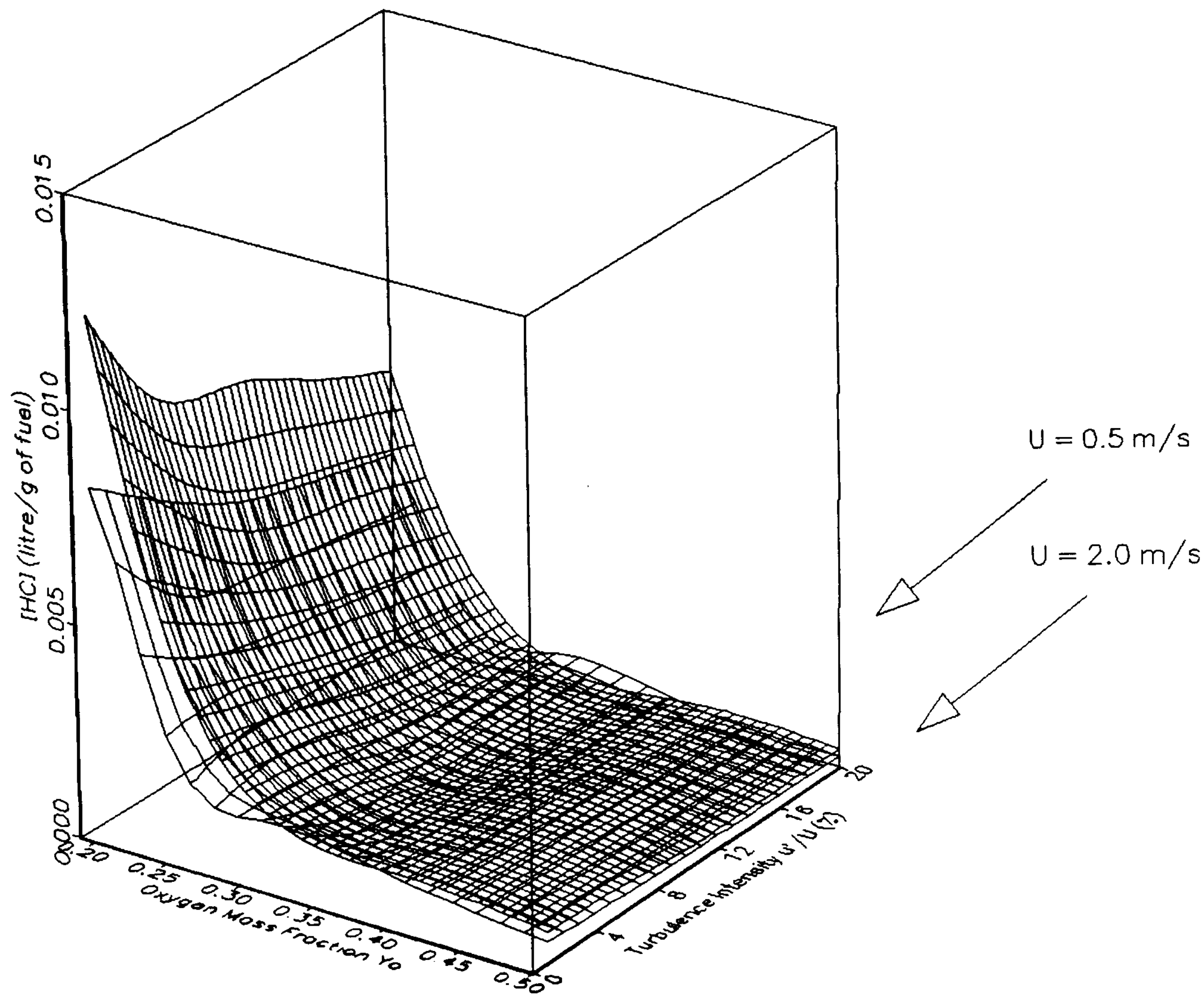

0.015
0.010
0.005
0.000
[HC] (litre/g of fuel)
0.20 0.25 0.30 0.35 0.40 0.45 0.50
Oxygen Mass Fraction Yo
0 4 8 12 18 20
Turbulence Intensity u'/U (%)
U = 0.5 m/s
U = 2.0 m/s

Fig. 15

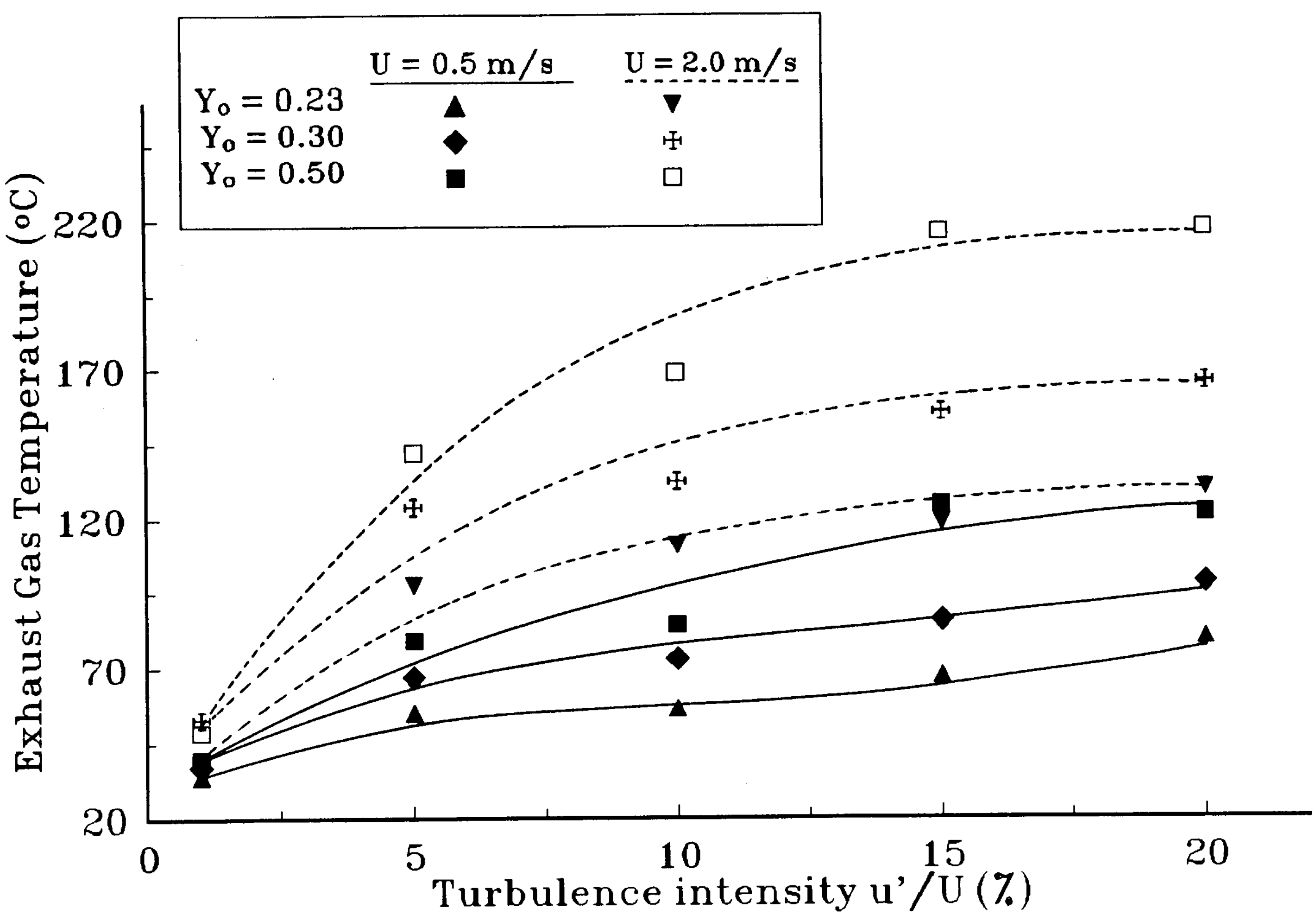

U = 0.5 m/s
U = 2.0 m/s
Yo = 0.23
Yo = 0.30
Yo = 0.50
Exhaust Gas Temperature (oC)
220
170
120
70
20
0
5
10
15
20
Turbulence intensity u'/U (%)

Fig. 16

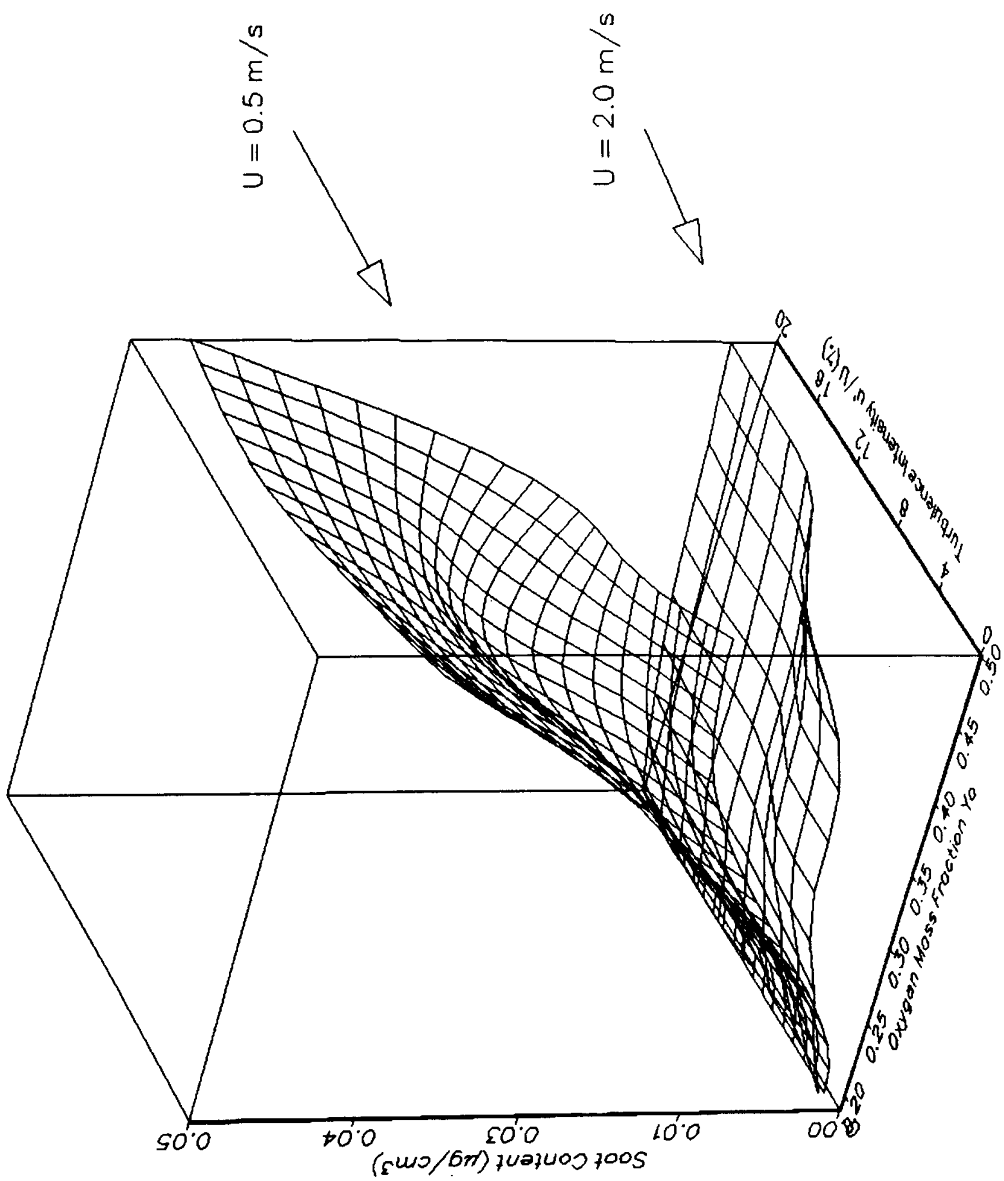

U = 0.5 m/s
U = 2.0 m/s
Soot Content (μg/cm3)
0.00
0.01
0.03
0.04
0.05
Oxygen Mass Fraction Yo
0.20
0.25
0.30
0.35
0.40
0.45
0.50
Turbulence Intensity u'/U(%)
0
4
8
12
18
20

Fig. 17

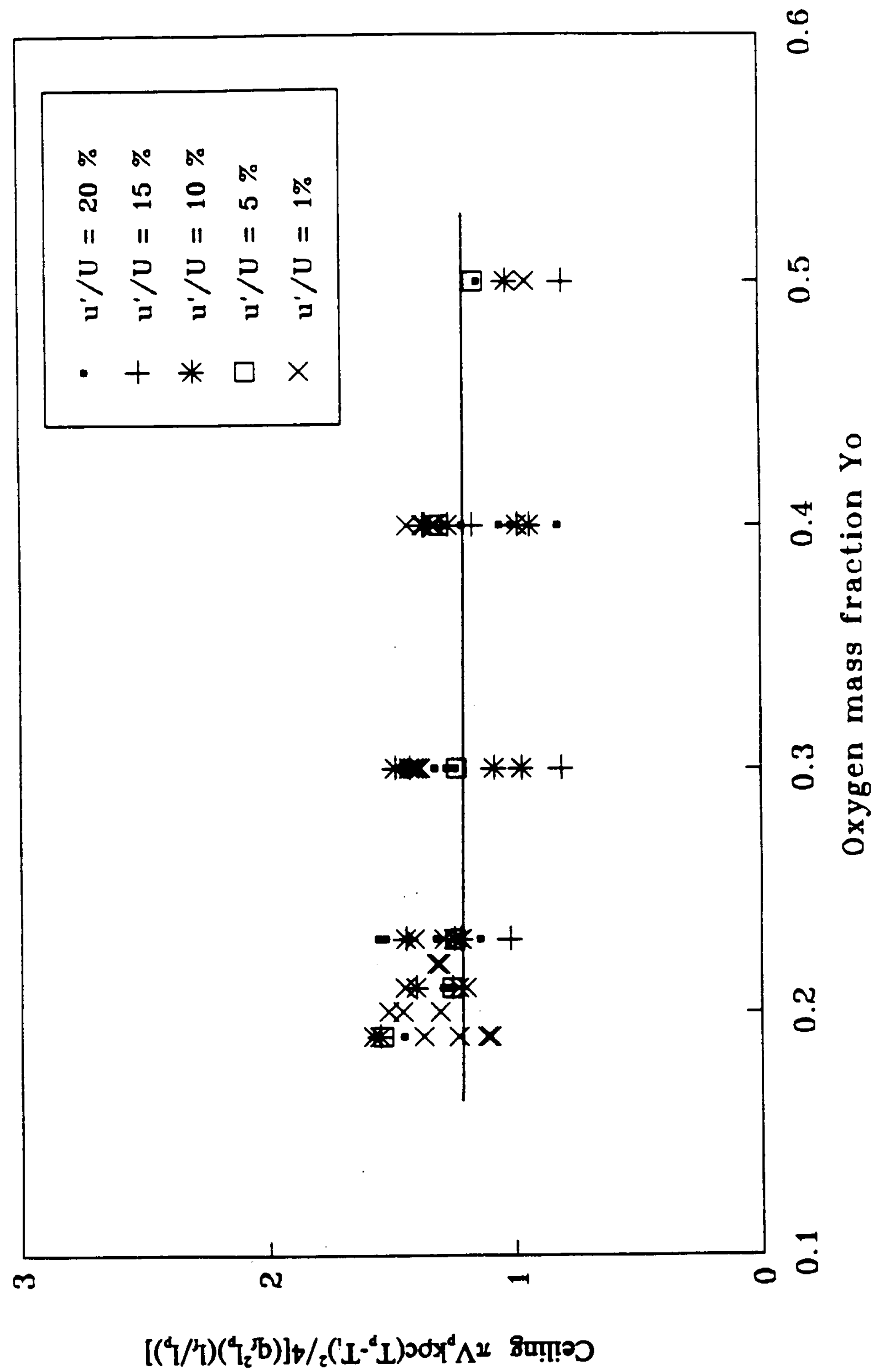

u'/U = 20 %
u'/U = 15 %
u'/U = 10 %
u'/U = 5 %
u'/U = 1%
0.1
0.2
0.3
0.4
0.5
0.6
Oxygen mass fraction Yo
0
1
2
3
Ceiling $\pi V_p k\rho c(T_p-T_i)^2/4[(q_r^2 L_p)(L_f/L_p)]$

Fig. 18

APPENDICES

A. Chao, Y.H. and Fernandez-Pello, A.C. "Flame Spread in a Vitiated Concurrent Flow" Accepted for presentation at the Minisymposium on Heat and Mass Transfer in Fire and Combustion, 1992 ASME/AIChE National Heat Transfer Conference, San Diego, CA. August 1992.

B. Chao, Y.H. and Fernandez-Pello, A.C. "Turbulent Concurrent Flame Spread : Effect of Oxygen Concentration" Western State Section/The Combustion Institute, 1993 Spring Meeting, University of Utah, Salt Lake City, Utah.

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Book No. H00757—1992

FLAME SPREAD IN A VITIATED CONCURRENT FLOW

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ABSTRACT

Experiments have been conducted to study the effects of forced gas flow velocity and oxygen concentration on the flow assisted flame spread over a flat solid combustible surface. All the tests are performed with thick PMMA Sheets as fuel and mixtures of oxygen and nitrogen as oxidizer. The spread rate is measured for flow velocity ranging from 0.5 to 2.0 m/sec and oxygen mass fraction from 0.19 to 0.23. It is found that the flame spread rate increases linearly with the main flow velocity and the oxygen concentration within the experimental conditions. In order to determine the effect of buoyancy on the flame spread rate, data in the ceiling and floor configurations are compared. The exhaust gas composition are also measured to detect possible buoyancy effects on the chemical reactions in the flame. Despite the overall similarity between the characteristics of ceiling and floor surface flame spread, some substantial differences have been observed. The experimental results indicate that buoyancy has two main effects in the ceiling case, one is the enhancement of heat transfer from the flame to the solid surface, and the other is the flame quenching through cold wall effect. For large flow velocities, the enhanced heat transfer is found to be dominant and results in a faster flame propagation in the ceiling than in the floor. For low flow velocities, the flame quenching effect becomes more important and the opposite result is observed. The transition velocity decreases as the oxygen mass fraction decreases.

INTRODUCTION

The spread of fire is a problem of great interest in fire research and much work has been carried out to study the chemical and physical parameters that determine the flame spread process. Among the different modes of flame spread, the concurrent mode of flame spread is the fastest and most hazardous because the gas pushes the flame ahead of the burning region which enhances the heat transfer from the flame to the unburnt material and consequently the spread of the flame.

In concurrent flame spread, upstream from the pyrolysis front the solid fuel is pyrolyzed by the heat transfer from the flame. The vaporized fuel is diffused and convected outward and forward reacting with the ambient oxidizer and a diffusion flame is established in the boundary layer next to the solid surface. The fuel vapor that is not consumed in the upstream flame is convected downstream from the pyrolysis front where it keeps reacting with the oxidizer, extending the diffusion flame downstream. The onset of fuel pyrolysis determines the progress of the pyrolysis front and consequently the flame spread rate. Previous work on this subject is summarized in the review of Fernandez-Pello et al. (1983).

The most important and frequently studied controlling factors are chemical parameters such as fuel type, gas oxygen concentration, and flow conditions such as flow type, flow rate, turbulence intensity and buoyancy and other factors such as external radiation. Among these factors, the buoyancy and the flow oxygen concentration are often investigated both experimentally and numerically for their ubiquitous existence (Orloff et al. 1972, Orloff et al. 1975, Fernandez-Pello 1977, Loh et al. 1985, Sibulkin 1988). Previous work on buoyancy effect mostly dealt with vertical configuration and not much work has been done on horizontal configuration. The buoyancy effect can be studied by comparing the flame spread rate at the floor burning configuration and at the ceiling burning configuration. The controlling mechanism of ceiling flame spread have many similarities to those of the more frequently studied floor configuration except for the effect of gravity on the heat and mass transfer processes. For a diffusion flame spreading over a horizontal surface in the case of ceiling burning, the buoyancy effect drives the reaction zone upward, which enhances heat transfer to the solid, and also introduces the conditions that may inhibit the chemical reaction due to quenching effect. The buoyancy effects are especially evident under low flow velocity and low oxygen concentration conditions.

Recent work by Mekki et al. (1990) carried out a detailed experimental investigation of the laminar flow flame spread over wood and PMMA in the ceiling configuration. It is found that the flame spread rates for both materials vary nearly linearly with the free steam velocity. The flame spread rate for PMMA varies with the oxygen concentration at a power of 1.4. The expression contradicts results from previous experiments (Loh et al. 1985) which shows a quadratic dependence of flame spread rate on oxygen concentration. No buoyancy effect was considered in that work. This points out the need for further experimental investigation to determine which of the experiments or assumptions made are responsible for the observed discrepancies, and how buoyancy can affect the flame spread. It has been noticed that most of the works done on concurrent flame spread were on the side of high oxygen concentration and scarce fundamental information has been obtained on the low oxygen concentration conditions. Furthermore, fires in buildings often occur under vitiated conditions, and there is a need of further information about the spread of fire at low oxygen concentration.

The object of the present study is to carry out a systematic experimental study of both floor flame spread and ceiling flame spread under a low oxygen concentration flow at laminar condition.

EXPERIMENTAL ARRANGEMENT

The experimental apparatus is shown schematically in Fig. 1. It consists of a laboratory scale wind tunnel designed to conduct condensed fuel flame spread experiments under various flow conditions and the supporting instrumentation. The wind tunnel has a 0.89 m long settling chamber with a rectangular cross section 0.31 m by 0.18 m, which supplies air flow to the tunnel test section through a converging nozzle with an area reduction ratio of 5.6 to 1. The side walls of the test section are made of 6 mm Pyrex glass for visual observation and optical diagnostic access, and the floor and ceiling are made of 55 mm thick Marinite slabs. The exhaust section is 1.22 m long and connected to the test section. Four mixing plates of different shapes are placed inside the exhaust section to generate sufficient disturbance in the flow and produce uniform concentration profile. The combustion tunnel is mounted horizontally on a three axis positioning table, while the optical instrumentation is kept stationary.

The air flow in the test section is supplied from a centralized air compressor and nitrogen gas is supplied from gas cylinders. The amount of flow is controlled by critical nozzles. The oxygen concentration in the air is varied by mixing nitrogen into the main stream flow. The air flow velocity and turbulence intensity are measured with a one-component Laser Doppler Velocimeter operating in the dual-beam, forward scattering mode. The experimental installation also includes a Schlieren system with a 0.45 m diameter collimated light beam and an array of eight thermocouples placed evenly on the fuel surface along the centerline, which are used to measure and monitor the solid combustible surface temperatures. Gas analyzers are used to measure the concentrations of major species O_2, CO, CO_2, NO and unburned hydrocarbons in the exhaust gas flow.

The fuel specimens used in this work are made from 12.7 mm thick PMMA (polymethylmethacrylate) sheets manufactured by Rolm and Haas (Plexiglas G), with a dimension of 300 mm by 70 mm. PMMA is chosen because of its well-known and uniform properties and non-Charring burning. A fuel sample is placed flush in the Marinite ceiling or the floor of the tunnel test section with eight thermocouples embedded on its surface. The specimen is ignited at its upstream edge with an electrically heated Nichrom wire which initiates the flame spread over the

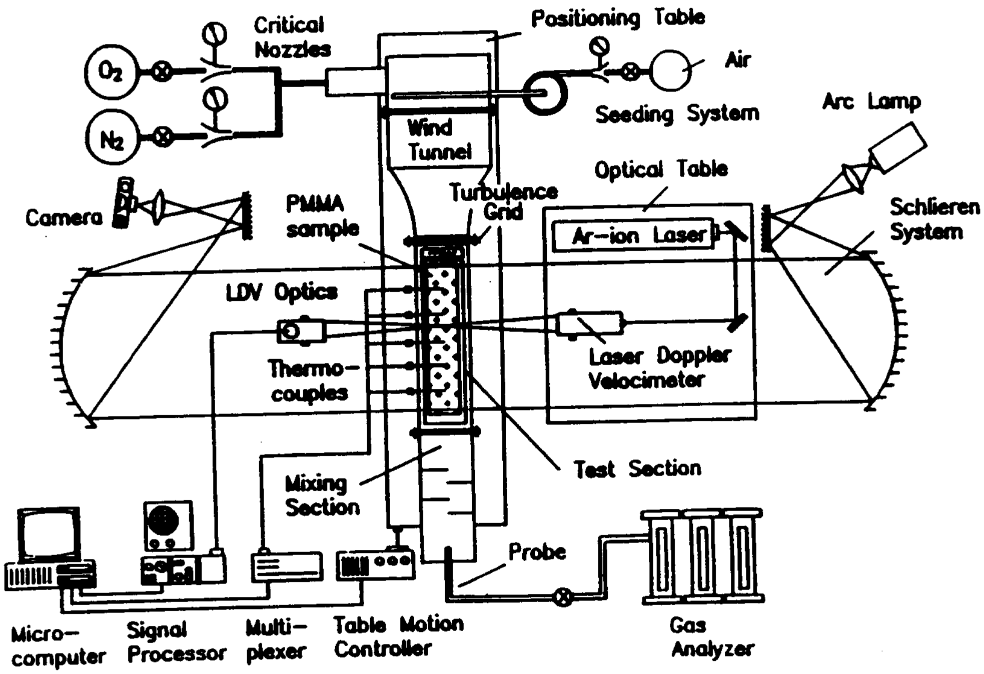

Fig. 1. Schematic drawing of the experimental apparatus.

length of the PMMA sheet. The flame spread rate is calculated from the time interval needed for the pyrolysis front to travel the fixed distance between two consecutive thermocouples, which can be deduced from the surface temperature histories measured. After the pyrolysis front has reached the last thermocouples, the combustion is extinguished with nitrogen in less than 20 seconds.

RESULTS AND DISCUSSION

The measured flame spread rate of PMMA sheet in ceiling and floor burning are shown in Fig. 2 to 5, as a function of free flow velocity ranging from 0.5 to 2.0 m/sec and oxygen mass fraction ranging from 0.19 to 0.23. The spread rate is an average of the values deduced from consecutive thermocouples throughout the specimen length and from two different tests. The flame spread rate is quite steady along the length of the specimen and the standard deviation is, in most cases, of the order of 7%. No data for oxygen mass fraction lower than 0.19 has been obtained because the spread of the flame could not be initiated or flame extinction occured after the flame had propagated for a short distance.

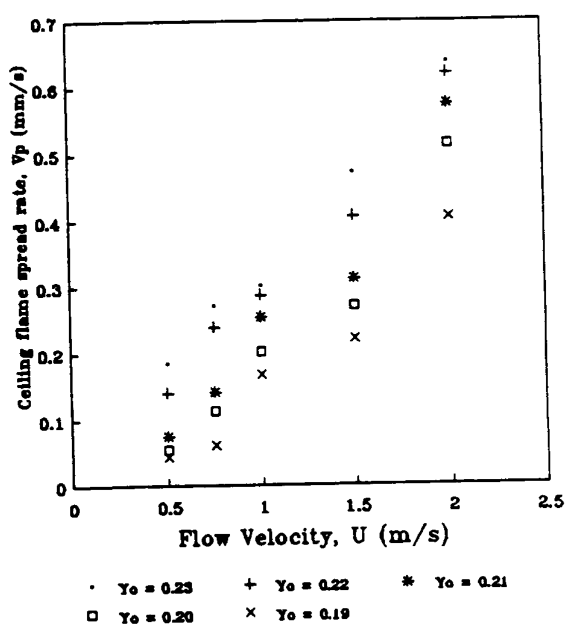

Fig. 2. Variation of ceiling flame spread rate with flow velocity at different oxygen mass fractions.

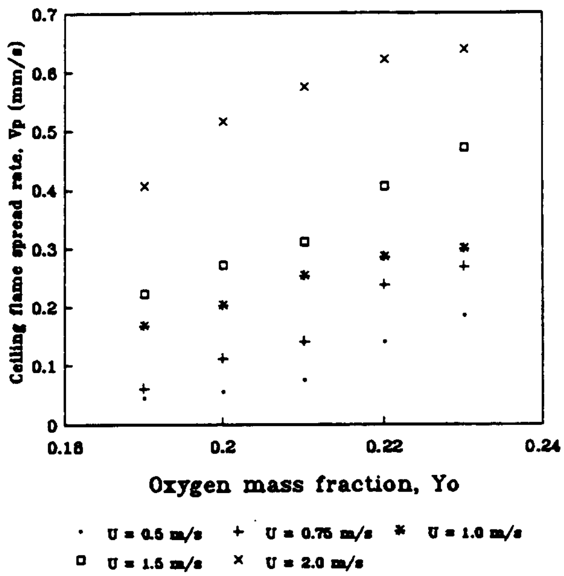

Fig. 3. Variation of ceiling flame spread rate with oxygen mass fraction at different flow velocities.

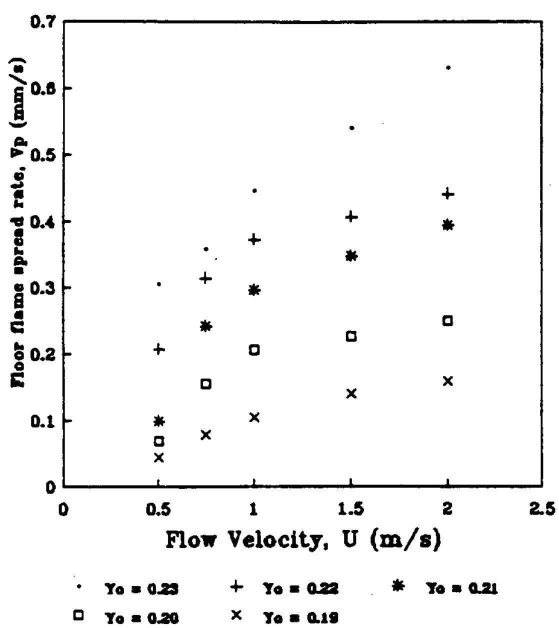

Fig. 4. Variation of floor flame spread rate with flow velocity at different oxygen mass fractions.

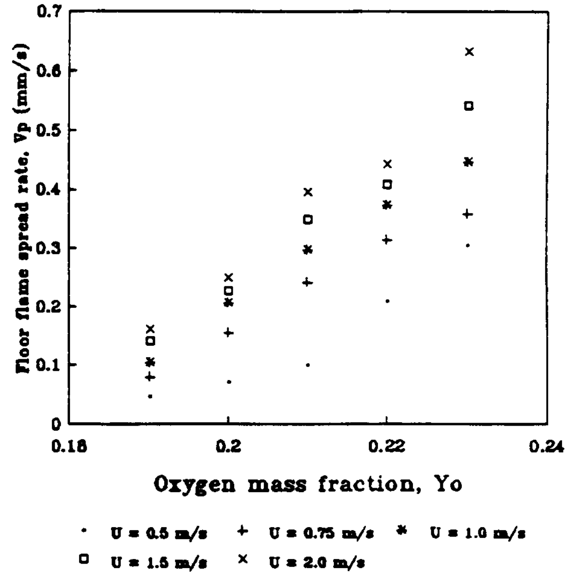

Fig. 5. Variation of floor flame spread rate with oxygen mass fraction at different flow velocities.

From the figures, It is seen that the flame spread rate varies approximately linearly with the flow velocity. As per the oxygen mass fraction for both ceiling and floor configurations, no clear trends are observed, although it appears that the spread rate varies approximately linearly with the oxygen mass fraction.

In order to understand the characteristics of the experimental results better, it is convenient to briefly examine the mechanisms of the flame spread. Previous experimental and theoretical work on the concurrent mode of flame spread indicate that heat transfer from the flame to the solid fuel is the dominant controlling mechanism (Fernandez-Pello et al. 1983, Loh et al. 1985, Zhou et al. 1990). An expression for the flame spread rate can be obtained by a simple energy analysis applied to a control volume in the unburnt solid downstream from the pyrolysis front (Quintiere 1981, Saito et al. 1986).

$$Vp = \frac{q^{2}_{f} l_{f}}{(Tp-Ti)^{2}} \qquad (1)$$

$$= \frac{(Tf-Tp)^2 U(l_f/l_p)}{(Tp-Ti)^2} \quad (2)$$

$$= \frac{Yo^2 U(l_f/l_p)}{(Tp-Ti)^2} \quad (3)$$

where Vp is the flame spread rate, Tf is the flame temperature, Tp is the pyrolysis temperature, Ti is the initial solid temperature, U is the flow velocity, q_f is the heat flux from the flame to the solid fuel and l_f is the flame length, which is defined as the distance between the pyrolysis front and the point where the heat transfer from the flame to the specimen starts.

Effort has been made to normalize the data by plotting $Vp(T_p-T_i)^2/(q_f^2 l_p)(l_f/l_p)$ against U and the results are shown in Fig.6 and 7. $q_f^2 l_p$ and l_f/l_p are calculated from the temperature history of the specimen. It is found that $Vp(T_p-T_i)^2/(q_f^2 l_p)(l_f/l_p)$ is nearly a constant for different values of U and Yo. It provides a further validation for the simple energy analysis used here to determine the flame spread rate.

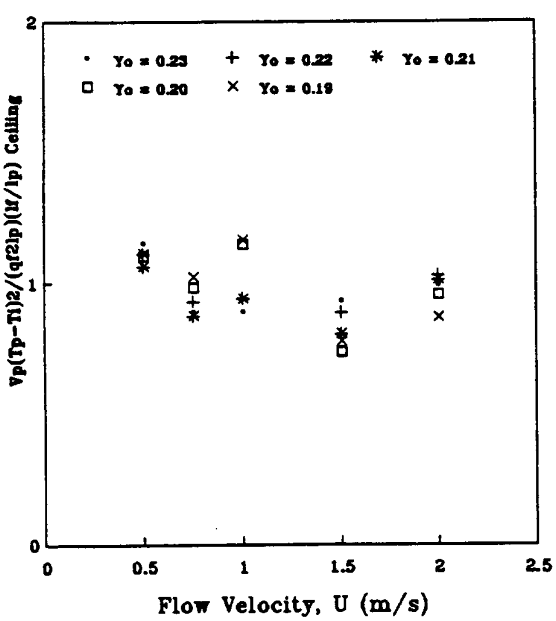

Fig. 6. Correlation of the ceiling flame spread data in terms of a non-dimensional flame spread rate deduced from Eq. (1).

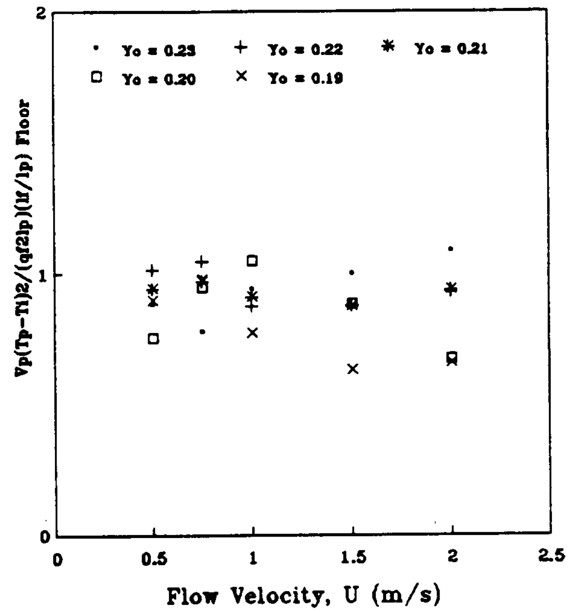

Fig. 7. Correlation of the floor flame spread data in terms of a non-dimensional flame spread rate deduced from Eq. (1).

The theoretical model predicts that Vp varies linearly with U and quadratically with Yo. The latter seems contradictory to the experimental result that Vp varies linearly with Yo. One point that needs special attention is that in deriving equation (3), the flame chemical reaction is assumed to be complete. However, the experiments in the present study were conducted at low enough oxygen concentration conditions that incomplete combustion occurs, and so it is not suitable to simply assume that q_f is linearly proportional to Yo. Another factor which may affect the dependence of Vp on Yo is the ratio, l_f/l_p. For combustion process at high oxygen concentration, it is usually assumed that l_f/l_p is independent of the oxygen mass fraction according to previous experimental results (Loh et al. 1985, Mekki et al. 1990). However, whether the same assumption can be made under low oxygen concentration condition is debatable. Therefore, more work has to be done to determine the relationship between q_f and Yo and that between l_f/l_p and Yo at low oxygen concentration condition in order to explain the discrepancy between the previous theoretical model and the present experimental results.

In order to further investigate the importance of chemical kinetics in determining the flame spread rate and comparing the difference between ceiling burning and floor burning under low oxygen concentration conditions, concentrations of major species O_2, CO, CO_2 , NO and unburnt hydrocarbons in the exhaust gas flow were measured. A good indication of the completeness of the combustion is the CO and unburnt hydrocarbons concentrations, thus they have been plotted against different flow conditions and oxygen mass fractions in Fig. 8 to 11. The gas concentrations were measured when the pyrolysis front has reached 270 mm downstream from the ignition point. The less complete reaction will go with higher concentrations of CO and unburnt hydrocarbons. From these measurements, it can be concluded that the chemical reactions are less complete at lower oxygen mass fraction and lower main flow velocity conditions. It can also be noticed that the reaction is less complete in the ceiling configuration than in the floor configuration, which agrees with previous experimental works (Zhou et al. 1991).

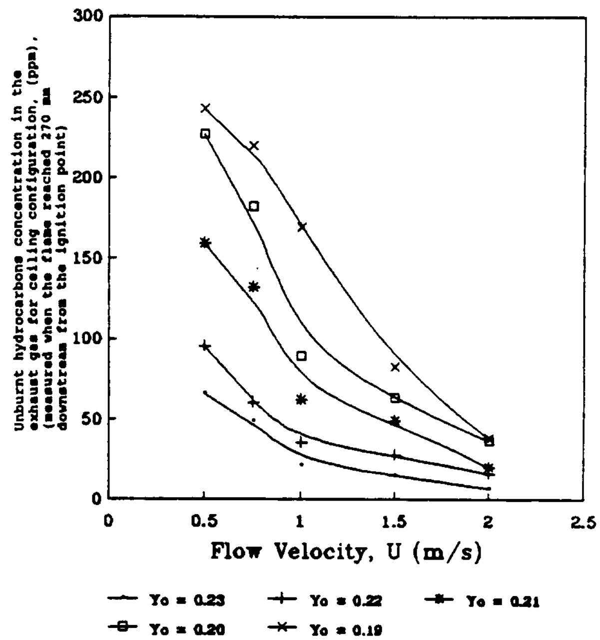

Fig. 9. Variation of Unburnt hydrocarbons concentration in the exhaust gas with flow velocity at ceiling configuration under different oxygen mass fractions.

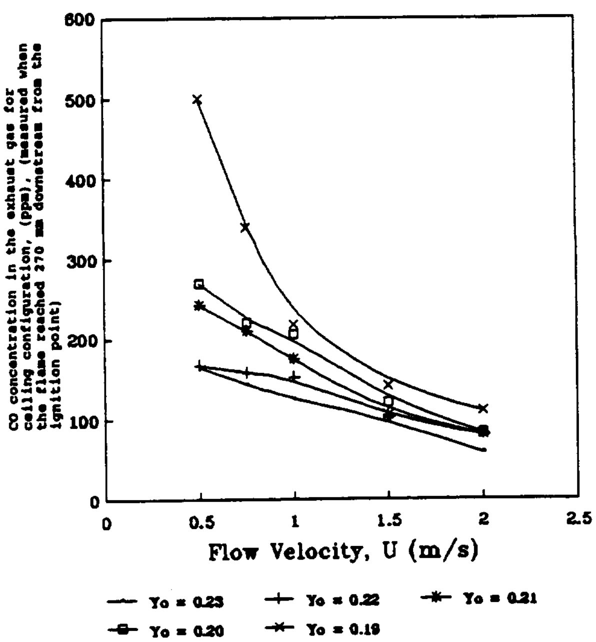

Fig. 8. Variation of CO concentration in the exhaust gas with flow velocity at ceiling configuration under different oxygen mass fractions.

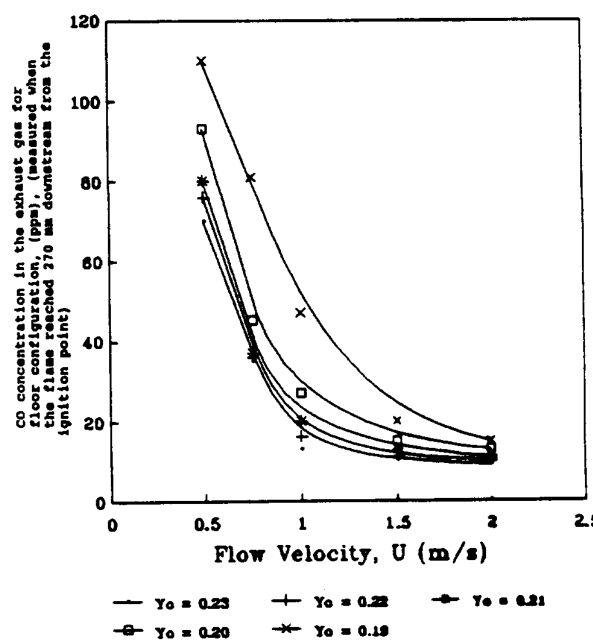

Fig. 10. Variation of CO concentration in the exhaust gas with flow velocity at floor configuration under different oxygen mass fractions.

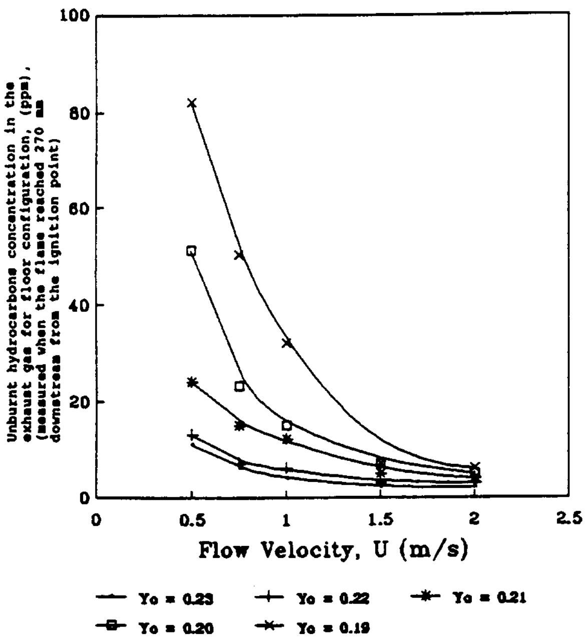

Fig. 11. Variation of unburnt hydrocarbons concentration in the exhaust gas with flow velocity at floor configuration under different oxygen mass fraction.

The main difference between ceiling and floor flame spread is caused by buoyancy effects. In the ceiling flame spread, the hot fuel vapor stays at the top and cold air stays under the flame to form a relatively stable layer that hinders the mixing processes and it is possible that there is insufficient oxygen in the reaction to proceed completely. In the floor flame spread, the buoyancy force lifts the hot gas upward favoring the mixing of the fuel vapor and the oxidizer, and it can be expected that a more complete reaction can be attained. This phenomenon is particularly evident at low flow velocity and low oxygen concentration cases.

Furthermore, in the ceiling case, buoyancy force pushes the flame closer to the fuel surface, which produces two opposite effects. It enhances the heat transfer from the flame to the fuel and can lower the flame spread rate due to quenching effect (Zhou et al. 1991). From the experimental results shown in Fig. 2 to 5, it is found that when the free flow velocity is larger than 1.5 m/s, the enhanced heat transfer effect dominates and thus the flame spread rate at ceiling case is higher than that at floor case. When the free flow velocity is less than 1.5 m/s, quenching effect dominates and the flame spread rate at the ceiling is less than that at the floor due to larger heat losses. The transition velocity seems to decrease when the oxygen mass fraction is decreased. For example, when Yo is larger than 0.21, the transition velocity is around 1.5 m/s. When Yo is 0.20, the transition velocity is in between 1.0 m/s and 1.5 m/s. When Yo is 0.19, the transition velocity is in between 0.75 m/s and 1.0 m/s. Thus it appears that the transition velocity is a function of the oxygen mass fraction.

CONCLUDING REMARKS

The results of this study show that oxidizer flow velocity and oxygen concentration have a strong influence on the flame spread rate under both ceiling and floor configurations. The experimental results indicate that the flame spread rate has a linear relationship with the oxygen level and flow velocity when the fuel is burnt at low oxygen concentration and low flow velocity conditions. This may have a significant impact in fire modeling because flame spread rate under vitiated conditions is important in the development of room fire models.

The experiments further indicate that apart from the heat transfer model which has frequently been used in describing concurrent flame spread over a solid fuel, chemical kinetics may be a key factor in determining flame spread rate under low oxygen concentration conditions. In order to resolve the discrepancy between theoretical model and the experimental results, relationship between heat flux and oxygen mass fraction and relationship between flame length and oxygen mass fraction at low oxygen level must be obtained.

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TURBULENT CONCURRENT FLAME SPREAD : EFFECT OF OXYGEN CONCENTRATION

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Western State Section/ The Combustion Institute, 1993 Spring Meeting, University of Utah, Salt Lake City, Utah. Paper # 93S-19

factors such as external radiation. Previous work mostly dealt with vertical configuration [6, 7] and not much work has been done on horizontal configuration .

The buoyancy effect can be studied by comparing the flame spread rate at the floor burning configuration and at the ceiling burning configuration. The controlling mechanism of ceiling flame spread have many similarities to those of the more frequently studied floor configuration except for the effect of gravity on the heat and mass transfer processes. For a diffusion flame spreading over a horizontal surface in the case of ceiling burning, the buoyancy effect drives the reaction zone upward, which enhances heat transfer to the solid, and also introduces the conditions that may inhibit the chemical reaction due to quenching effect. The buoyancy effects are especially evident under low flow velocity and low oxygen concentration conditions.

In contrast to the abundance of research performed on flame spread rate over laminar flow condition, not much work has been done on turbulent flow condition. Recently Zhou et al. [8-9] conducted tests on thick PMMA sheets at turbulent flow condition. It is found that with air, turbulence intensity decreases the flame spread rate due to an apparent decrease of the flame length. To the best knowledge of the authors, no experiment has been conducted to investigate the combined effects of turbulence and oxygen concentration on the flame spread rates.

The scare information currently available on the controlling mechanisms of turbulent flame spread and the potential significance of such knowledge in fire prevention and protection have provided the main incentives for conducting the present study. The objective here is to carry out a systematic experimental study of both floor and ceiling flame spread under different flow velocity, oxygen concentration and turbulence intensity conditions to investigate how these factors affect the flame spread rate.

EXPERIMENTAL ARRANGEMENT

The experimental apparatus is shown schematically in Fig. 1. It consists of a laboratory scale wind tunnel designed to conduct condensed fuel flame spread experiments under various flow conditions and the supporting instrumentation. The wind tunnel has a 0.89 m long settling chamber with a rectangular cross section 0.31 m by 0.18 m, which supplies air flow to the tunnel test section through a converging nozzle with an area reduction ratio of 5.6 to 1. The side walls of the test section are made of 6 mm Pyrex glass for visual observation and optical diagnostic access, and the floor and ceiling are made of 55 mm thick Marinite slabs. The exhaust section is 1.22 m long and connected to the test section. Four mixing plates of different shapes are placed inside the exhaust section to enhance flow mixing and produce uniform concentrations. The combustion tunnel is mounted horizontally on a three axis positioning table, while the optical instrumentation is kept stationary.

The oxidiser flow in the test section is supplied from a centralized air compressor, and oxygen and nitrogen gases are supplied from gas cylinders. The amount of flow is controlled by critical nozzles. The flow oxygen concentration is varied by mixing nitrogen and air or oxygen into the main stream flow. Turbulence is introduced to the flow by means of perforated plates which are placed perpendicular to the flow direction at the exit of the tunnel converging nozzle. The air flow velocity and turbulence intensity are measured with a one-component Laser Doppler Velocimeter operating in the dual-beam, forward scattering mode. The experimental installation also includes a Schlieren system with a 0.45 m diameter collimated light beam and an array of eight thermocouples placed evenly on the fuel surface along the centerline, which are used to measure and monitor the solid combustible surface temperatures. Gas analyzers are used to measure the concentrations of major species O_2, CO, CO_2, NO and unburned hydrocarbons in the exhaust gas flow. Soot coming out from the combustion process is collected by a Pallflex fiberfilm filter (#T60A20 and size 47 mm) and amount of soot is determined by measuring the weight difference of the filter before and after the experiment using a high precision balance.

The fuel specimens used in this work are made from 12.7 mm thick PMMA (polymethylmethacrylate) sheets manufactured by Rolm and Haas (Plexiglas G), with a dimension of 300 mm by 70 mm. PMMA is chosen because of its well-known and uniform properties and non-Charring burning. A fuel sample is placed flush in the Marinite ceiling or the floor of the tunnel test section with eight thermocouples embedded on its surface. The specimen is ignited at its upstream edge with an electrically heated Nichrom wire which initiates the flame spread over the length of the PMMA sheet. The flame spread rate is calculated from the time interval needed for the pyrolysis front to travel the fixed distance between two consecutive thermocouples, which can be deduced from the surface temperature histories measured. After the pyrolysis front has reached the last thermocouples, the combustion is extinguished with nitrogen in less than 20 seconds.

RESULTS AND DISCUSSION

The measured flame spread rates over PMMA sheet in ceiling burning are shown in Fig. 2 to 3, for oxygen mass fractions ranging from 0.19 to 0.50, and at different turbulence intensities. The spread rate is an average of the values deduced from consecutive thermocouples throughout the specimen length and from two different tests. No data for oxygen mass fraction lower than 0.23 has been obtained for turbulent cases because the spread of the flame could not be initiated or flame extinction occured after the flame had propagated for a short distance. Floor burning shows similar trend and is not shown here.

From Figures 2 and 3, it is found that at low flow velocity (U = 0.5 m/s), turbulence increases the flame spread rate significantly at high oxygen concentration. At high flow velocity (U > 1.0 m/s), as the turbulence is increased, the flame spread rate increases initially and then decreases as the turbulence intensity is further increased. The flame spread rate increases monotonically with flow velocity and oxygen mass fraction for all turbulence intensities.

In order to understand the characteristics of the experimental results better, it is convenient to briefly examine the mechanisms of the flame spread. Previous experimental and theoretical work on the concurrent mode of flame spread indicate that heat transfer from the flame to the solid fuel is the dominant controlling mechanism [3, 10, 11]. An expression for the flame spread rate can be obtained by a simple energy analysis applied to a control volume in the unburnt solid downstream from the pyrolysis front [12].

$$V_p = \frac{q^2 l_f}{(T_p - T_i)^2} \tag{1}$$

$$= \frac{q^2 l_p (l_f / l_p)}{(T_p - T_i)^2} \tag{2}$$

where V_p is the flame spread rate, T_p is the pyrolysis temperature, T_i is the initial solid temperature, U is the flow velocity, q is the heat flux from the flame to the solid fuel and l_f is the flame length, which is defined as the distance between the pyrolysis front and the point where the heat transfer from the flame to the specimen starts.

The heat flux q from the flame to the fuel surface can be further modeled approximately as :

$$q = (K + K_T) \frac{T_f - T_p}{\delta} + q_r \qquad (3)$$

where K is the heat transfer coefficient for laminar flow and K_T is the contribution from turbulence intensity (eddy diffusivity), T_f is the flame temperature which is a function of both oxygen mass fraction and turbulence intensity, δ is the thermal boundary layer thickness which is a function of the main flow velocity, and q_r is the thermal radiation term which comes mainly from soot.

Equation (1) and (2) shows that oxygen mass fraction, flow velocity and turbulence intensity can affect the flame spread rate primarily through the surface heat flux and the flame length.

In this work, the flame length and heat flux have been determined from the solid surface temperature histories. Their relation to the pyrolysis length is an important aspect of the flame spread problem. In the work carried out by Zhou et al. [10], power law correlations between the flame length, pyrolysis length and heat flux have been found :

$$l_f = a l_p^b \qquad (4)$$

$$q^2 l_p^c = d \qquad (5)$$

where a, b, c and d are functions of flow velocity and turbulence intensity. Coefficients b and c are close to unity within the experimental conditions.

Relations (4) and (5) also apply at different oxygen concentrations as shown in Fig. 4 - 5, although it is found that oxygen mass fraction increases the l_f/l_p ratio. At U = 0.5 m/s, turbulence increases lf/lp ratio monotonically but at U = 2.0 m/s, l_f/l_p ratio rises with turbulence at the beginning and goes down if we further increase the turbulence level. Similar trend has been found for the heat flux term $q^2 l_p$ and they are shown in Fig. 6 - 7.

In order to further investigate the importance of chemical kinetics in determining the flame spread rate, concentrations of major species O_2, CO, CO_2 , NO and unburnt hydrocarbons in the exhaust gas flow were measured. A good indication of the completeness of the combustion is the CO and unburnt hydrocarbons concentrations. The variation of CO with oxygen mass fraction at different turbulence intensities is shown in Fig. 8 - 9. The unburnt hydrocarbon concentration shows a similar trend and it is not shown here. From these measurements, it can be concluded that the completeness of the chemical reactions is very sensitive to oxygen concentration. The combustion completeness increases strongly with oxygen concentration at low oxygen content. It can also be noticed that in general, turbulence lowers the degree of combustion completeness but the difference is less significant at high oxygen concentration. In general, ceiling burning has a higher CO and unburnt hydrocarbon concentration than floor burning.

Measurements of the soot concentration in the exhaust gas is used to provide insight on the soot produced and its potential effect on thermal radiation. The result is shown in Fig 10 - 11. It is found that at low flow velocity (U = 0.5 m/s), turbulence increases the amount of soot but the opposite trend is observed for higher velocity range (U = 2.0 m/s). In general, amount of soot increases with oxygen mass fraction and flow velocity for all turbulence intensities.

The above results indicate that the interaction of turbulence and oxygen concentration plays an important role in the l_f/l_p ratio and the heat flux term $q^2 l_p$, which in term affect the flame spread rate. Turbulence has several effects in the flame spread rate. Increasing flow turbulence reduces the flow stratification and enhances the combustion by vigorous mixing; this increases the flame temperature and thus heat transfer to the fuel surface. On the other hand, turbulence also has a quenching effect through cold air mixing and cold wall effect. The relative importance of these effects depend on the oxygen concentration. The flame spread characteristics depend on which of the above effects is dominant. Equation (3) can be used to explain the observed dependence of l_f/l_p and $q^2 l_p$ on the turbulence intensity. At a fixed flow velocity and oxygen concentration, combustion completeness does not change much by varying the turbulence intensities especially when Yo is greater than 0.23. Is is then reasonable to assume that the flame temperature T_f is independent of the turbulence intensity. Then the only parameters which can affect the heat flux term is K_T and q_r. Turbulence increases the value of K_T through enhanced mixing although it seems to have different impact at different velocity ranges. Turbulence increases soot production at low flow velocity but decreases it at high flow velocity. Soot plays a significant role in thermal radiation effect especially at high oxygen concentration because of the high flame temperature. Turbulence affects soot concentration which in turns affects the radiant heat flux. At high flow velocity, the result is a competition between the convective heat transfer enhancement due to eddy diffusivity and the reduction in radiant flux due to decrease in soot concentration. This competition is more dominant at high oxygen concentration. This may help to explain why the heat flux increases monotonically with turbulence intensity at low flow velocities but not at high flow velocity.

The main difference between ceiling and floor flame spread is caused by buoyancy effects. In the ceiling flame spread, the hot fuel vapor stays at the top and cold air stays under the flame to form a relatively stable layer that hinders the mixing processes and it is possible that there is insufficient oxygen in the reaction to proceed completely. In the floor flame spread, buoyancy lifts the hot gas upward favoring the mixing of the fuel vapor and the oxidizer, and it can be expected that a more complete reaction would be attained. This phenomenon is particularly evident at low flow velocity and low oxygen concentration cases.

Furthermore, in the ceiling case, buoyancy force pushes the flame closer to the fuel surface, which produces two opposite effects. It enhances the heat transfer from the flame to the fuel and can also lower the flame spread rate due to quenching effect. The flame spread rate depends on which of the above parameters is more dominating [9].

CONCLUDING REMARKS

The results of this study show that the interaction of flow velocity and turbulence and of oxygen concentration has a strong influence on the flame spread rate under both ceiling and floor configurations. The experimental results indicate that turbulence increases the flame spread rate monotonically at low flow velocities but the trend is not that clear at high flow velocity. Turbulence affects soot concentration which in turns affects the radiant heat flux. At high flow velocity, the result is a competition between the convective heat transfer enhancement due to eddy diffusivity and the decrease in radiant flux due to decrease in soot concentration. The competition is more apparent at high oxygen concentration. This is of particular importance in the theorectical modeling of flame spread since most current works assume that thermal radiation effect can be neglected. In general, turbulence lowers combustion completeness but the difference seems to be small when oxygen mass fraction is greater than 0.23.

ACKNOWLEDGEMENT

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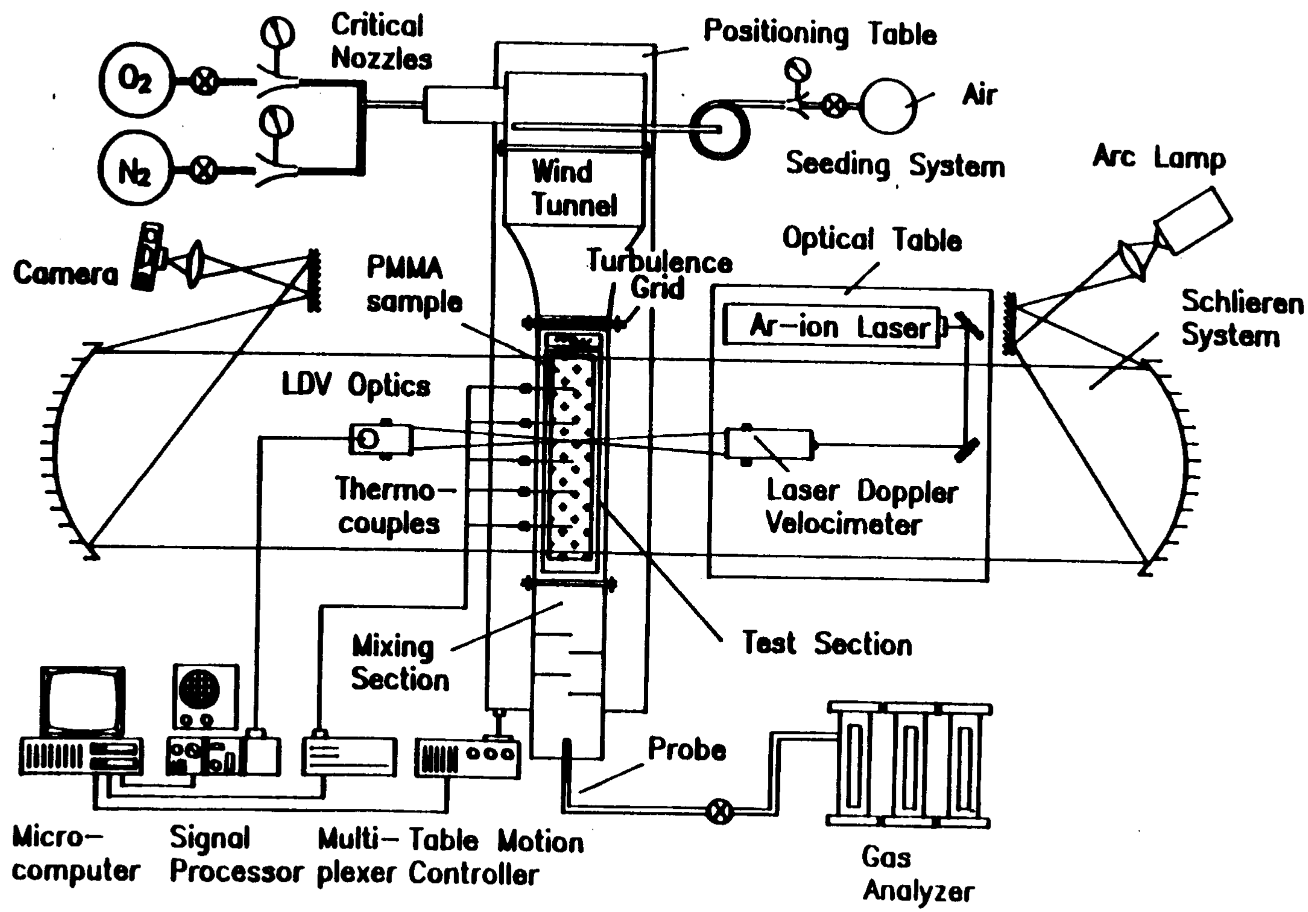
LIST OF FIGURES



Experimental Facility

Fig. 1

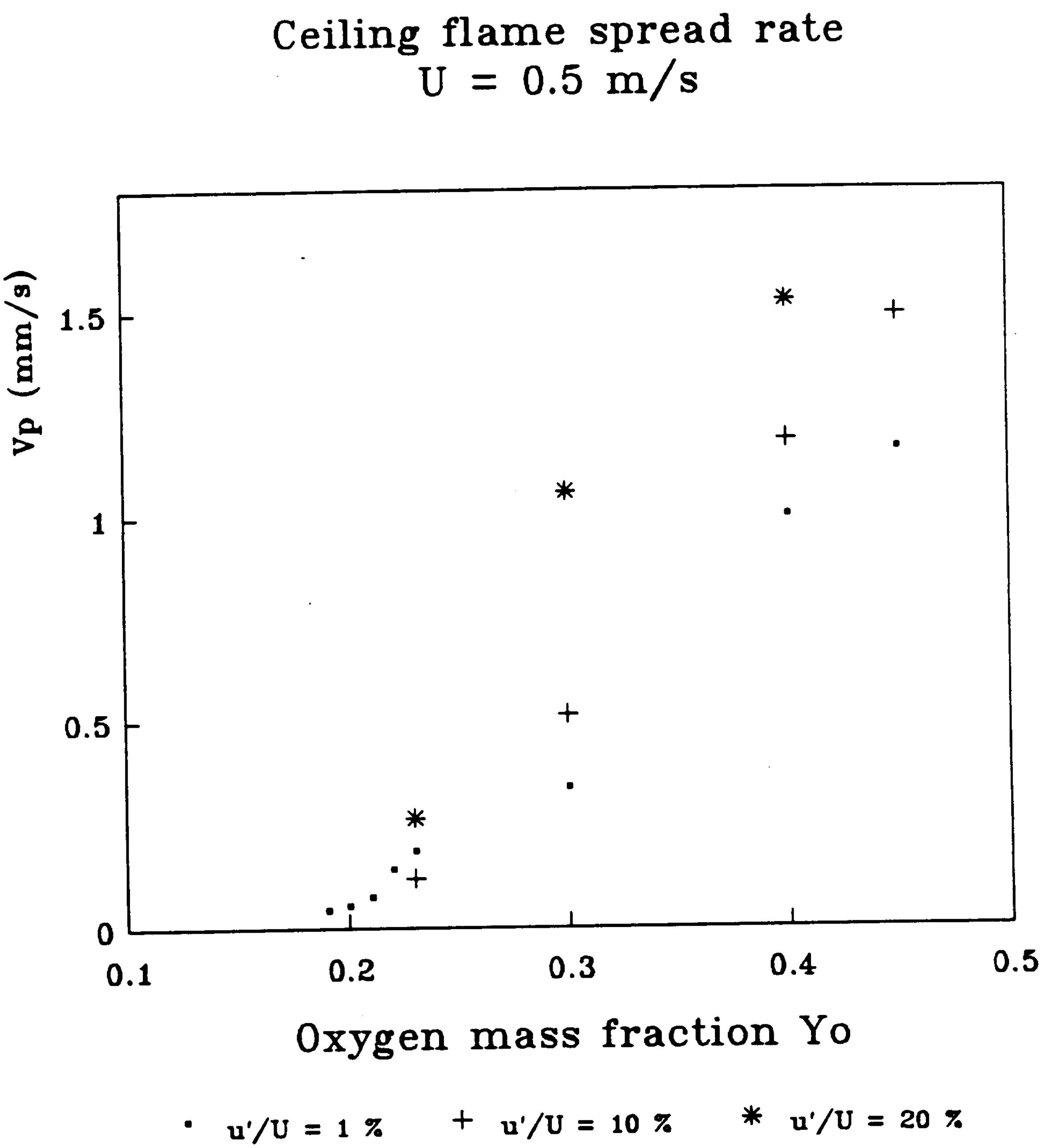

Ceiling flame spread rate
U = 0.5 m/s
Vp (mm/s)
1.5
1
0.5
0
0.1
0.2
0.3
0.4
0.5
Oxygen mass fraction Yo
u'/U = 1 %
u'/U = 10 %
u'/U = 20 %

Fig. 2

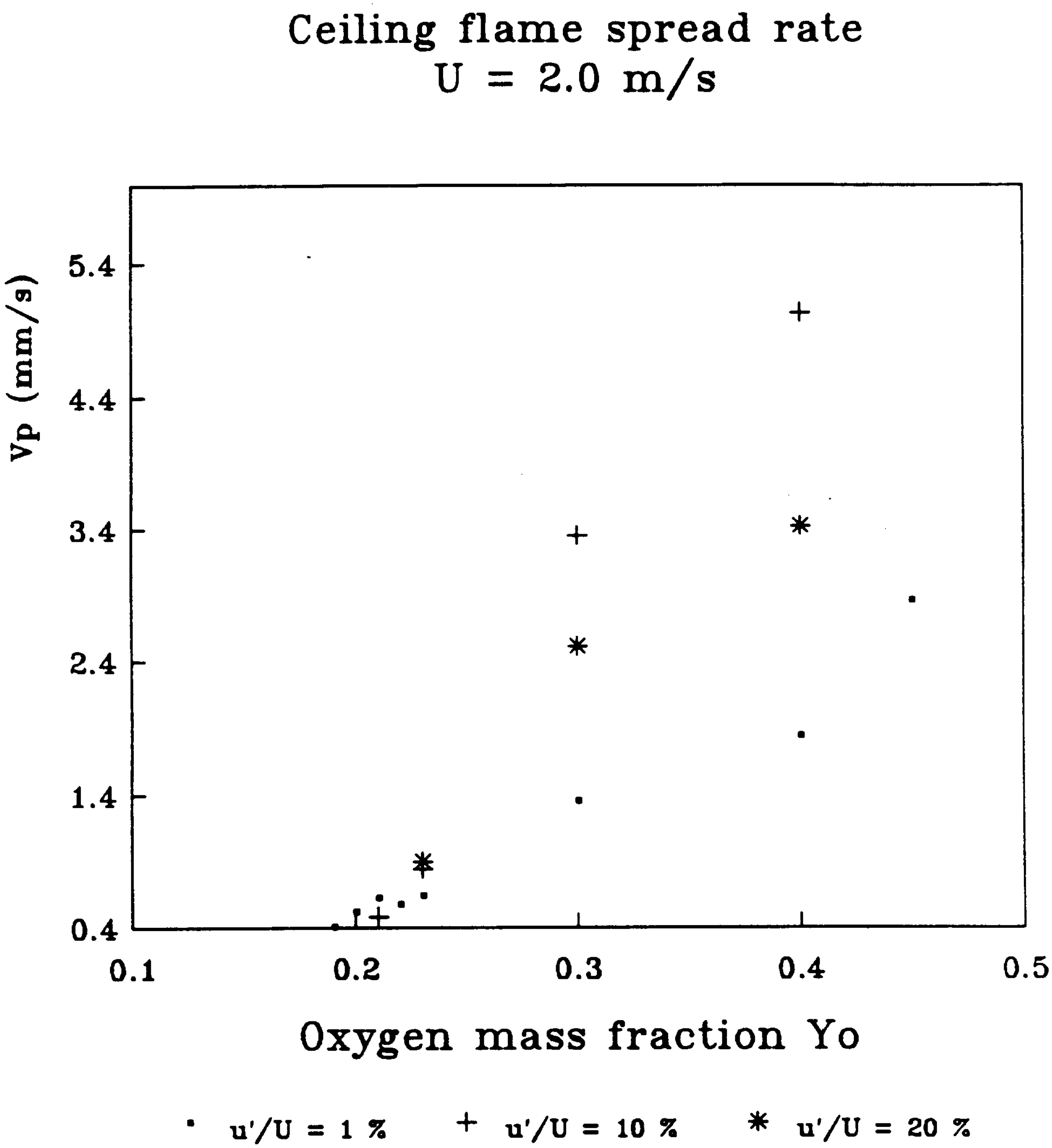

Ceiling flame spread rate
U = 2.0 m/s
Vp (mm/s)
5.4
4.4
3.4
2.4
1.4
0.4
0.1
0.2
0.3
0.4
0.5
Oxygen mass fraction Yo
u'/U = 1 %
u'/U = 10 %
u'/U = 20 %

Fig. 3

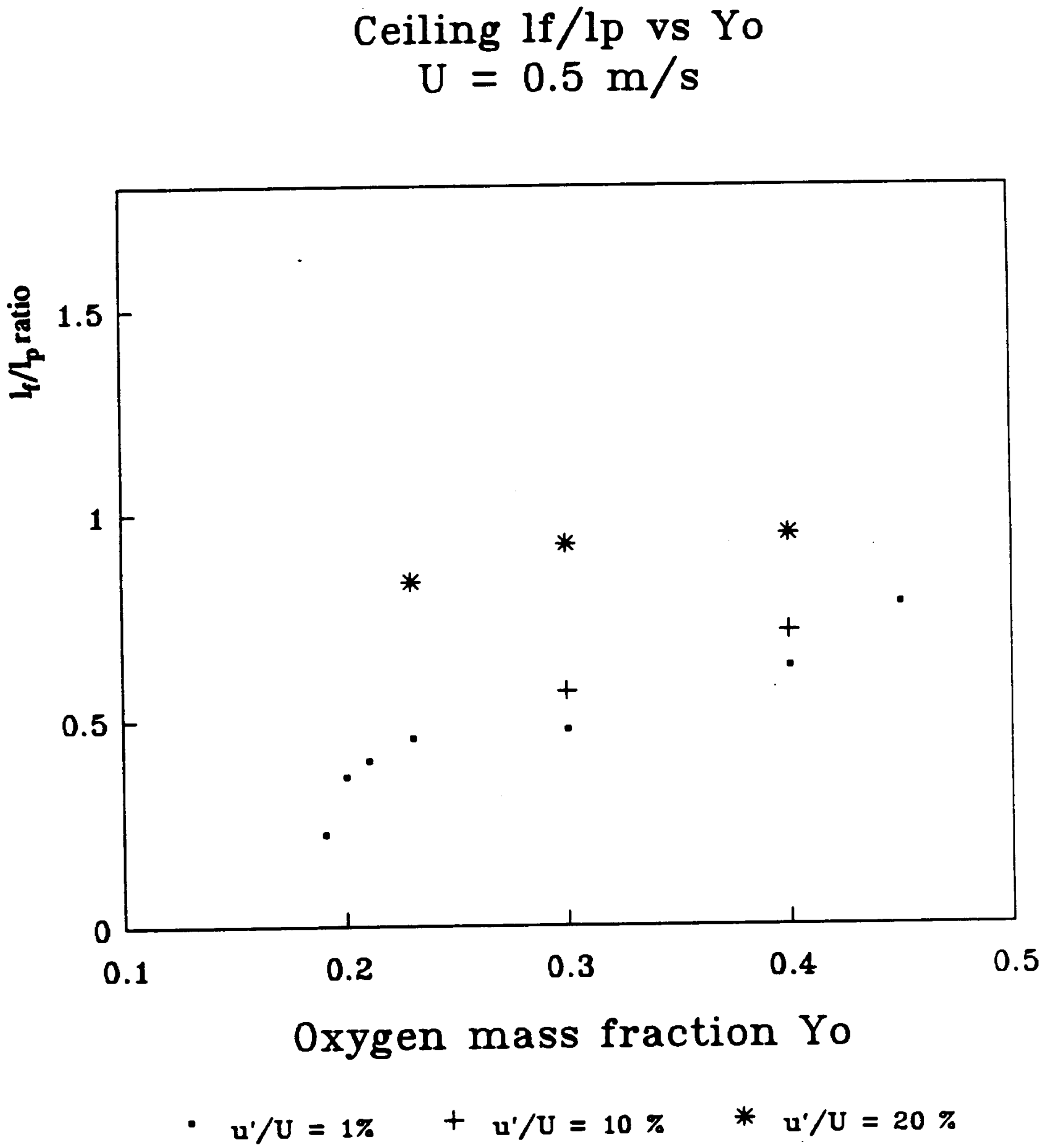

Ceiling lf/lp vs Yo
U = 0.5 m/s
l_f/l_p ratio
1.5
1
0.5
0
0.1
0.2
0.3
0.4
0.5
Oxygen mass fraction Yo
u'/U = 1%
u'/U = 10 %
u'/U = 20 %

Fig. 4

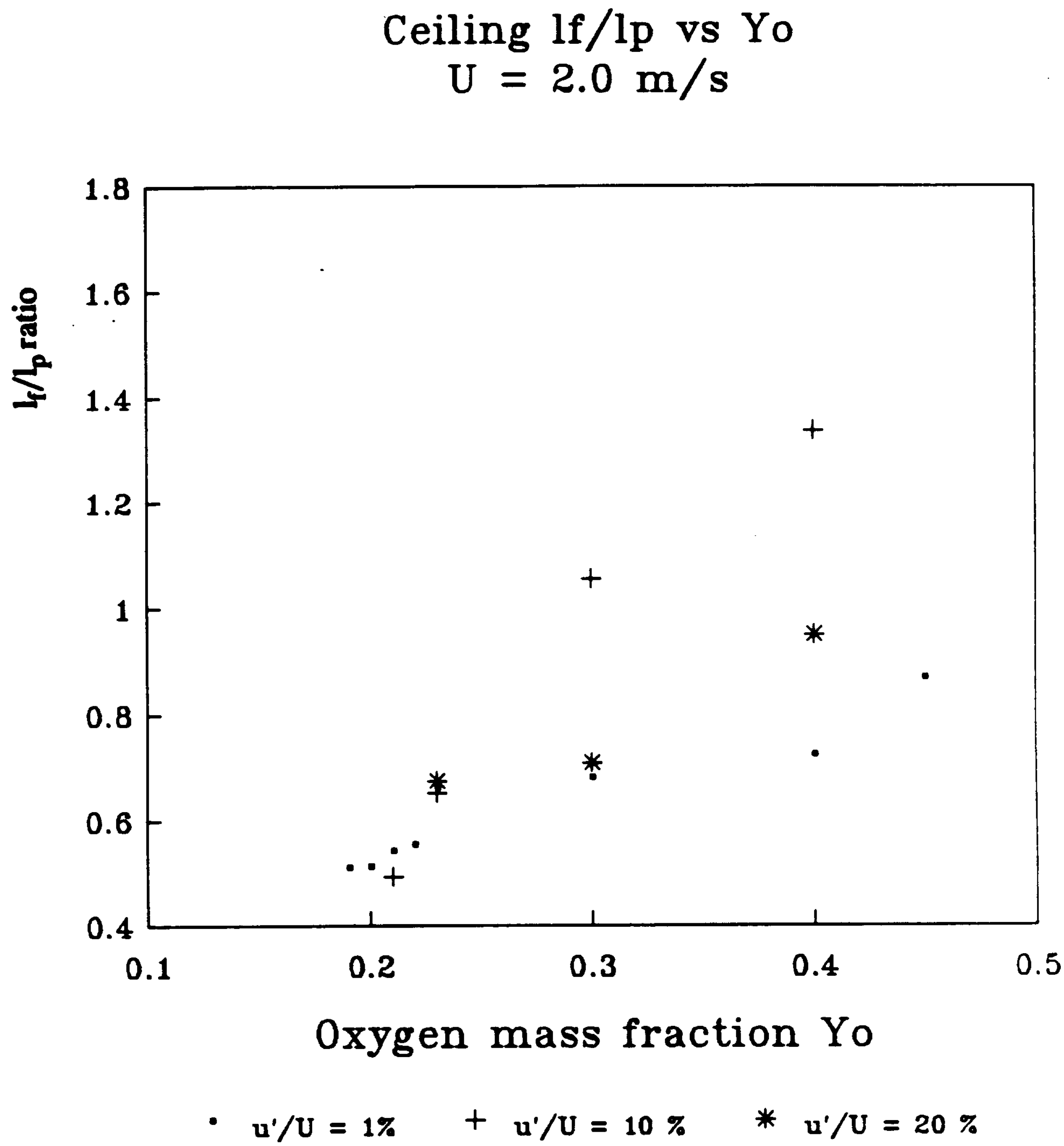

Ceiling lf/lp vs Yo
U = 2.0 m/s
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
lf/lp ratio
0.1
0.2
0.3
0.4
0.5
Oxygen mass fraction Yo
u'/U = 1%
u'/U = 10 %
u'/U = 20 %

Fig. 5

# Ceiling q2lp vs Yo
U = 0.5 m/s

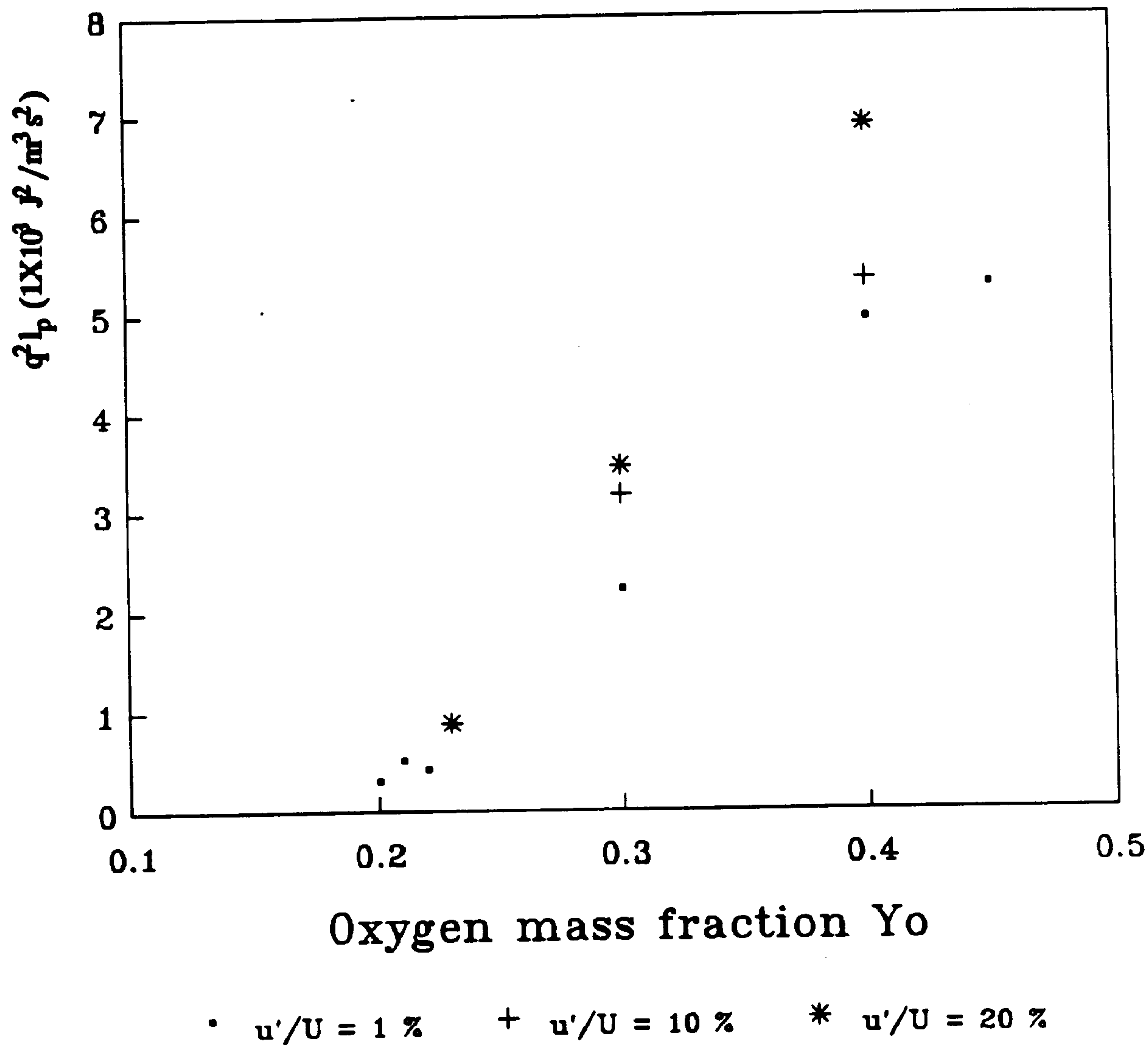


Fig. 6

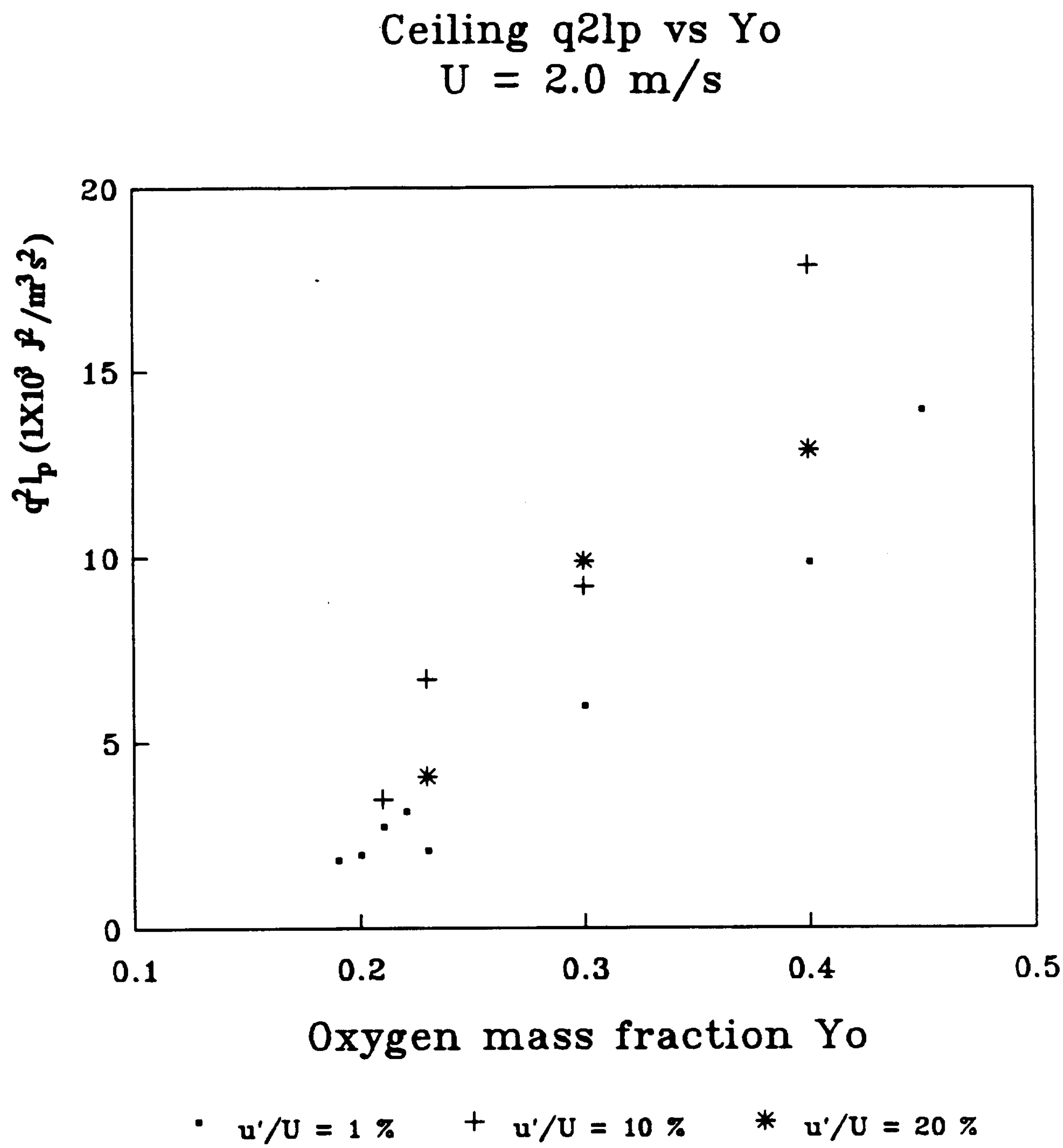

Ceiling q2lp vs Yo
U = 2.0 m/s
20
15
10
5
0
0.1
0.2
0.3
0.4
0.5
q^2l_p (1X10^3 J^2/m^{3}s^2)
Oxygen mass fraction Yo
u'/U = 1 %
u'/U = 10 %
u'/U = 20 %

Fig. 7

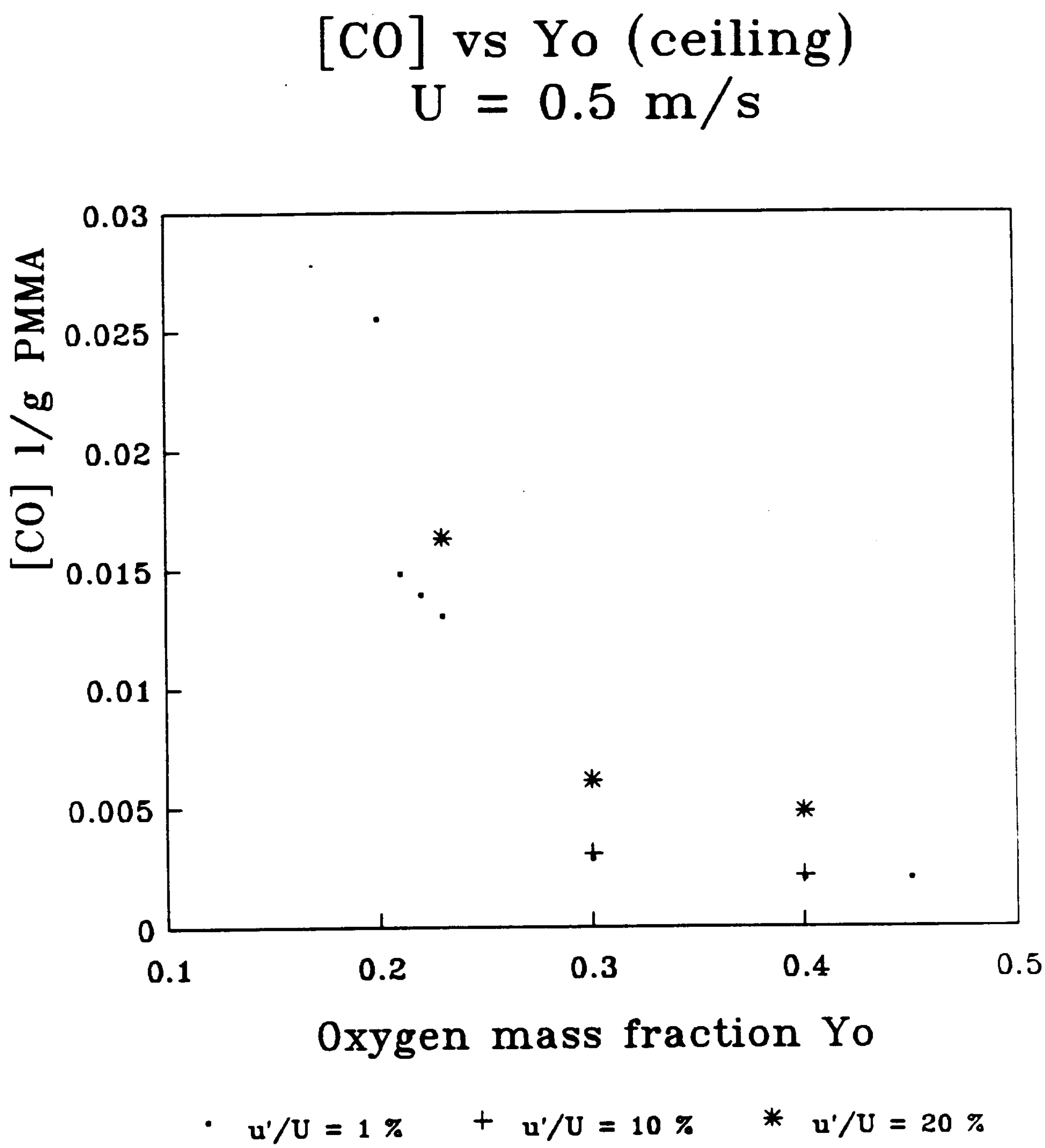

[CO] vs Yo (ceiling)
U = 0.5 m/s
0.03
0.025
0.02
0.015
0.01
0.005
0
[CO] l/g PMMA
0.1
0.2
0.3
0.4
0.5
Oxygen mass fraction Yo
u'/U = 1 %
u'/U = 10 %
u'/U = 20 %

Fig. 8

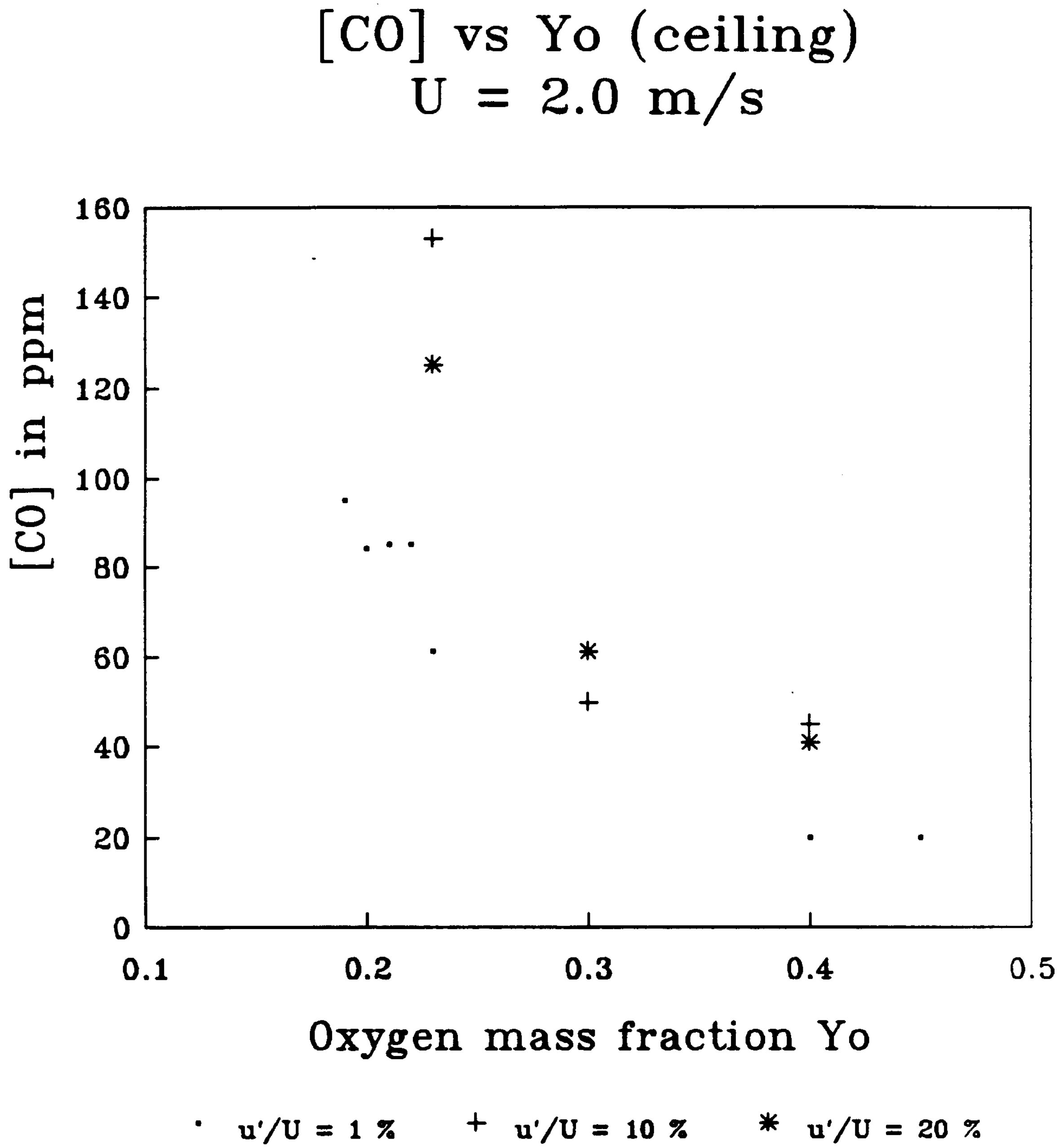

[CO] vs Yo (ceiling)
U = 2.0 m/s
[CO] in ppm
0
20
40
60
80
100
120
140
160
0.1
0.2
0.3
0.4
0.5
Oxygen mass fraction Yo
u'/U = 1 %
u'/U = 10 %
u'/U = 20 %

Fig. 9

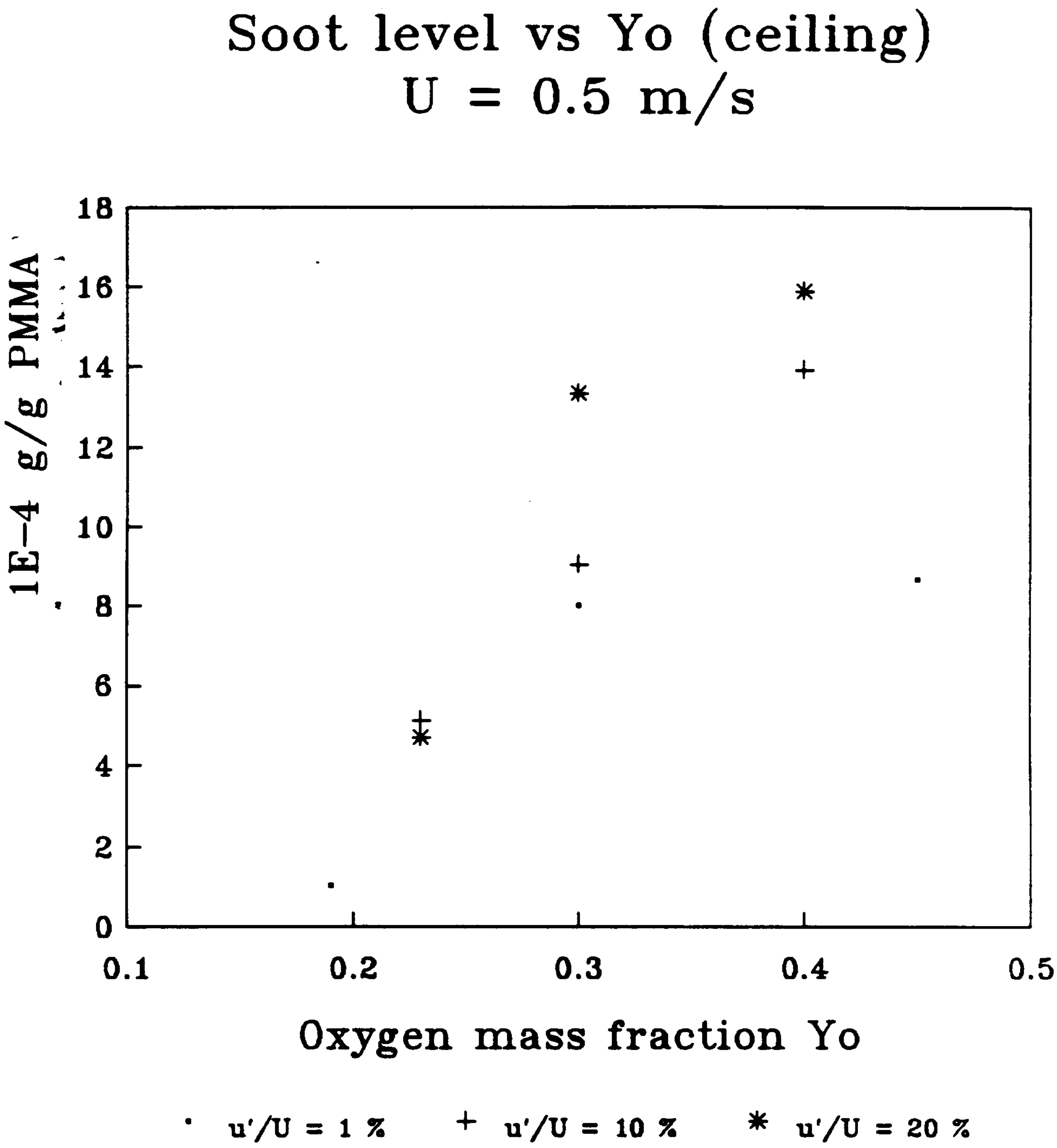

Soot level vs Yo (ceiling)
U = 0.5 m/s
1E-4 g/g PMMA
18
16
14
12
10
8
6
4
2
0
0.1
0.2
0.3
0.4
0.5
Oxygen mass fraction Yo
· u'/U = 1 %
+ u'/U = 10 %
* u'/U = 20 %

Fig. 10

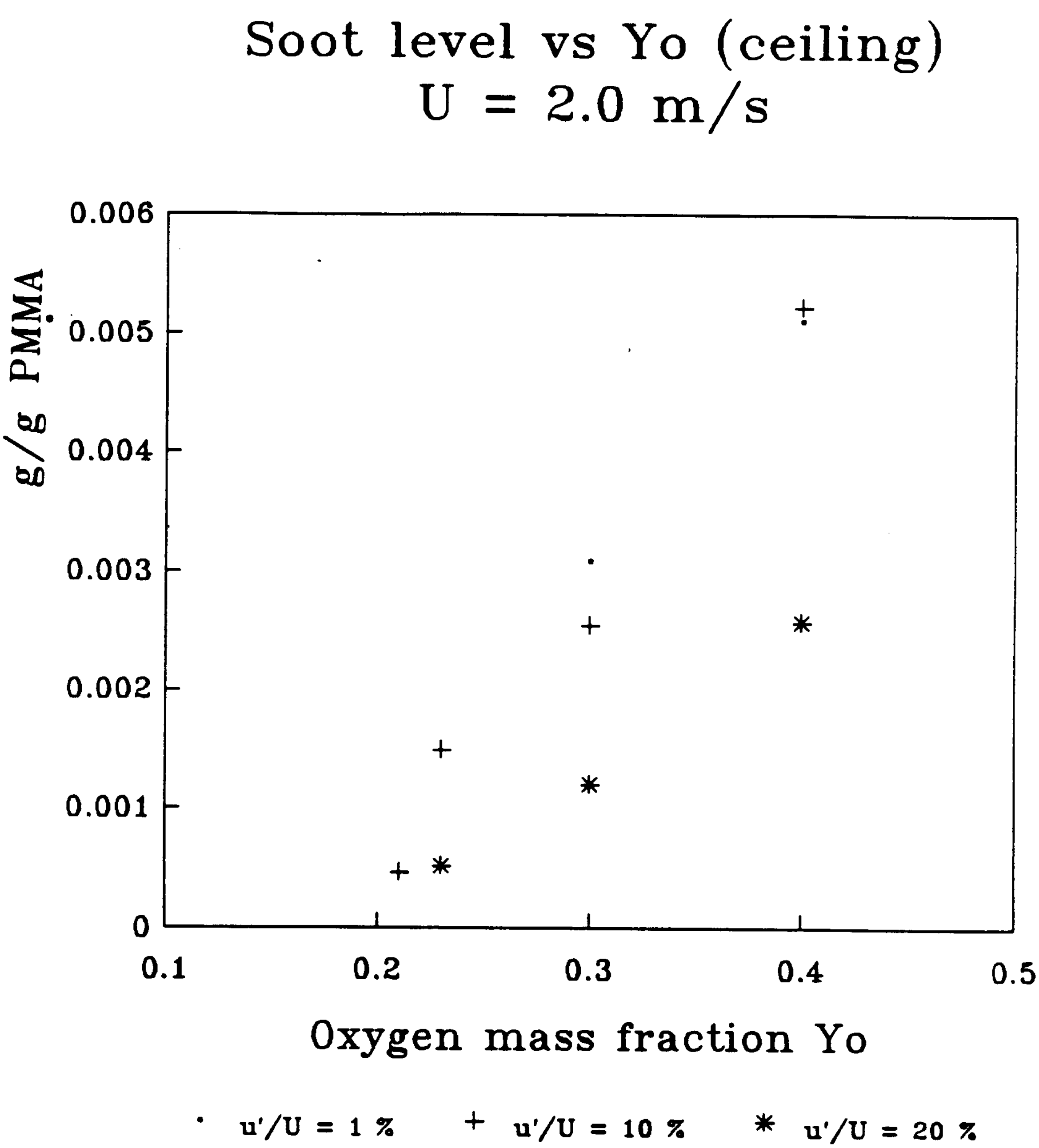

Soot level vs Yo (ceiling)
U = 2.0 m/s
g/g PMMA
0.006
0.005
0.004
0.003
0.002
0.001
0
0.1
0.2
0.3
0.4
0.5
Oxygen mass fraction Yo
u'/U = 1 %
u'/U = 10 %
u'/U = 20 %

Fig. 11

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A research program is being conducted to study the mechanisms controlling the spread of flames in an oxidizing gas flow moving in the direction of flame propagation. During this reporting period research has been conducted to study the effect of the oxidizer flow characteristics on the concurrent flame spread over thick PMMA sheets. The parameters varied in the experiments are the oxidizer flow velocity, turbulence intensity and oxygen concentration, and the geometrical orientation (floor and ceiling). Their effect on the flame spread process is studied by measuring the rate of flame spread, flame length, surface heat flux, products of combustion and soot. The results of the experiments show that the combined effect of flow velocity, turbulence intensity, and oxygen concentration has a complex influence on the flame spread process. At low flow velocity, the flame spread rate increases monotonically with turbulence intensity. At high flow velocity, however, the flame spread rate increases with flow turbulence at low turbulence intensities, but it decreases at high turbulence intensity values. The effect is more pronounced at high oxygen concentration. These trends appear to be due to a strong influence of the turbulence intensity on the flame temperature and length, and on the heat flux from the flame to the solid fuel. Turbulence enhances mixing, which increases the flame temperature and then the heat flux. The effect of turbulence on the flame length comes from two opposing factors. In one hand the enhanced mixing results in a stronger reaction with faster reactant consumption, which tends to produce a shorter but hotter flame. On the other hand, the higher flame temperature results in an increased mass burning rate, which tends to increase the flame length. By comparing the floor and ceiling results, it is found that buoyancy has two opposite effects, one is enhancing the heat transfer to the surface by reducing the flame stand-off distance and the other reducing the chemical reaction completeness by intensifying the flame quenching at the wall. The overall buoyancy effect on the flame spread and mass burning processes depends on the flow condition.

KEY WORDS (MAXIMUM OF 9; 28 CHARACTERS AND SPACES EACH; SEPARATE WITH SEMICOLONS; ALPHABETIC ORDER; CAPITALIZE ONLY PROPER NAMES)

Buoyant Flow; Fire Research; Flame Size; Flame Spread; Polymethylmethacrylate; Turbulent Burning; Turbulent Flow; Turbulent Heat Transfer

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